



The technology and economics of recycling scrap rubber.

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THE TECHNOLOGY AND ECONOMICS
OF
RECYCLING SCRAP RUBBER

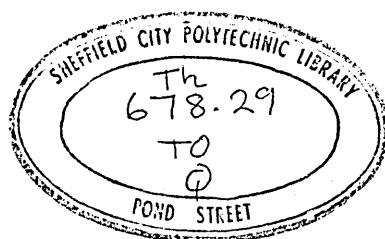
by

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ABSTRACT

The purpose of this project is to make a detailed technological and economic analysis of the current UK situation regarding the use of scrap rubber in order to identify the most effective processes and products. The scope of the investigation is restricted to the re-use of scrap rubber as a primary raw material for rubber product manufacture.

The thesis emphasises the following aspects : (i) the structure of the rubber processing industry and the role of the rubber recycling sectors; (ii) property relationships in rubber compounds incorporating scrap rubber crumb, with particular attention to material mechanics; (iii) the estimation of curing agent distribution in a crumb incorporated rubber vulcanizate; and (iv) the economics of the cryogenic grinding of scrap rubber tyres.

The property relationships of vulcanizates incorporating recycled rubber have been studied using several mathematical models : Gent, simple law of mixtures, Mooney-Rivlin models, and a non-Gaussian model based on a simplified form of inversed Langevin function. It was found that; (i) for some compounds the elastic modulus and strength could be described well by the law of mixtures for composites, (ii) the reduction in strength caused by the incorporation of crumb decreased with decreasing particle size but there is little advantage to be gained by reducing the size below 20 μm , (iii) different modes of failure may be operative, i.e. adhesive and cohesive, according to the strength of the matrix rubber.

The redistribution of curing agent in our whole tyre crumb-rubber vulcanizates has been studied using the SEM and EDAX techniques. Although qualitative and quantitative evidence for the migration of cure agent from matrix to crumb is given, no evidence was found for an interfacial layer between the two phases which is depleted of cure agent.

Little detailed information on the economics of the majority of commercially operated processes is available. Data has been obtained for the cryogenic grinding of scrap rubber, a technology which seems to show potential for commercial exploitation, and a thorough economic analysis performed. The result showed that, under currently depressed crumb prices and low demand, the most feasible of the plants considered is just marginally economically viable. It was found that the most important cost input to the cryogrinding process is the cost of cryogenic material (liquid nitrogen) and that the most important factor which governs the economic viability of the process is the price of the rubber crumb output. Socio-environmental and resource conservation factors indicate the desirability of Government support.

by

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SUMMARY

The purpose of this project is to make a detailed technological and economic analysis of the current situation regarding the use of scrap rubber in order to identify the most effective recycling processes and products. This work has taken a multi-disciplinary approach to the investigation of this highly relevant subject. Although particular emphasis has been given to the UK situation, a survey covering European and North American firms involved in this activity has been made.

The scope of the investigation is restricted to the re-use of scrap rubber as a primary raw material for product manufacture. This eliminates a number of rubber recycling options such as incineration and pyrolysis, and all the scrap rubber disposal procedures of which landfilling, traffic barriers and fish reefs are some examples.

The thesis emphasises the following aspects : (i) the structure of the rubber processing industry and the role of the rubber recycling sectors; (ii) property relationships in rubber compounds incorporating scrap rubber crumb, with particular attention to material mechanics; (iii) the estimation of cure agent distribution in a recycled rubber crumb incorporated rubber vulcanizate; and (iv) the economics of the cryogenic grinding of scrap rubber tyres.

The property relationships of rubber vulcanizates incorporating recycled rubber have been studied using data generated by our own experimental work, and the limited published data. The mathematical models used for this study were: (i) Gent model for relationship between the tensile strength and the effective particle size of the recycled rubber crumb, the tear energies and the initial moduli; (ii) the simple law of mixtures models for the relationship between elastic and strength properties of the vulcanizates and that of the recycled rubber and the matrix rubber compound, and the volume fraction of the incorporated recycled rubber; and (iii) the Mooney-Rivlin model and

a non-Gaussian model based on the Inverse Langevin Function for studying the stress-strain behaviours of these vulcanizates. Several important mechanisms governing the property relationships of these vulcanizates have been identified. The most important of which is the migration of curatives from the base rubber matrix into the vulcanized recycled rubber crumb particles.

The redistribution of sulphur curing agent for our whole tyre crumb-rubber vulcanizates has been studied using the SEM and EDAX techniques. Qualitative and Quantitative evidence has been obtained for this behaviour. Factors affecting the migration of sulphur have been identified, however further in-depth investigation is highly desirable in quantifying the influence of these factors.

Little detailed information on the economics of the majority of commercially operated processes is available. In this work data has been obtained for the cryogenic grinding of scrap rubber, a technology which seems to show potential for commercial exploitation, and a thorough economic analysis performed. The analysis consisted of conventional Discounted Cash Flow techniques of NPV and IRR, short and long term break-even analysis, and an investment simulation for the project. The simulation model offers a better representation of the real situation through the use of probability distribution to describe the variables involved. The results of the analyses showed that, under currently depressed rubber crumb prices and low demand, the most feasible of the four plant combinations considered is just marginally economically viable. However, the socio-environmental and resource conservation factors point towards the desirability of Government intervention.

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CONTENTS

<u>ABSTRACT</u>	ii
<u>SUMMARY</u>	iii
<u>ACKNOWLEDGEMENTS</u>	v
<u>CONTENTS</u>	vi
CHAPTER 1 <u>INTRODUCTION</u>	1
CHAPTER 2 <u>ANALYSIS OF THE RUBBER INDUSTRY AND MARKET</u>	5
2.1 Structure of Rubber Industry in UK	5
2.2 Sources, Forms and Supply of Rubber	10
(a) Sources and Forms	
(b) Supply and Consumption	
(c) Stock	
2.3 Rubber Consumption by Product	18
2.4 Historical Review of Rubber, Petroleum and Energy Costs	22
(a) Rubber Prices	
(b) Recycled Rubber Prices	
(c) Petroleum and Energy Costs	
CHAPTER 3 <u>SCRAP RUBBER ARISING IN THE UK</u>	28
3.1 Historical Review of the Scrap Rubber Industry	28
(a) Forms and Sources	
(b) Rubber Recycling Processes	
3.2 Statement and Analysis of Current Situation Regarding Scrap Rubber Arising	31
(a) The Uncured Scrap	
(b) Cured Scrap	
CHAPTER 4 <u>RUBBER RECYCLING PROCESSES : TECHNOLOGICAL CONSIDERATIONS</u>	35
4.1 Process Availability	35
A. Commercially Available Processes	36
(a) Conventional Reclamation Processes	
(b) Size Reduction Processes	
(c) Other	
B. Commercially Unavailable Processes	41
(a) Size Reduction Processes	
(b) Pyrolysis	
4.2 Forms of Input and Output	44
A. General Considerations	44
B. Inputs	47
C. Outputs	49

CHAPTER 5	<u>PHYSICAL PROPERTIES OF VULCANIZATES INCORPORATING RECYCLED RUBBER</u>	65
5.1	General Considerations	65
5.2	Previous Work	69
(a)	Elastic Properties	69
(b)	Strength Properties	78
(i)	Effect of recycled rubber crumb particle size	
(ii)	Effect of vulcanization system	
(iii)	Effect of volume fraction of recycled rubber filler	
(c)	Tear Resistance	91
(i)	Effect of hardness of recycled rubber filler	
(ii)	Effect of amount of recycled rubber filler	
5.3	Experimental	100
(a)	Compound Formulations and Material Manufacture	100
(b)	Test Procedure	102
5.4	Results and Discussion	103
(a)	Introduction	103
(b)	Elastic Properties	103
(c)	Strength Properties	109
(d)	Stress-Strain Behaviour and the Mechanics of Rubber-Rubber Composites	116
5.5	Conclusion	128
CHAPTER 6	<u>STUDIES OF CURATIVE DISTRIBUTION IN SULPHUR CURED COMPOUNDS INCORPORATING PARTICULATE SCRAP RUBBER</u>	131
6.1	General Considerations	131
6.2	Previous Work	132
6.3	Experimental Procedure	133
(a)	Specimen Preparation	135
(b)	SEM Operating Conditions	136
6.4	Results and Discussion	140
6.5	Conclusion	156
CHAPTER 7	<u>RUBBER RECYCLING PROCESSES : ECONOMIC CONSIDERATIONS</u>	158
7.1	General Considerations	158
7.2	Development Costs	159
7.3	Process Economics : Cost Factors Involved	160
A.	Capital Costs	160
(a)	Capital equipment and installation costs	
(b)	Working Capital	
(c)	Land and Building Costs	
B.	Operating Costs	164
(a)	Variable Costs	
(b)	Fixed Costs	
C.	Pricing of Recycled Rubber	166

D.	Other Costs	168
	(a) Tax	
	(b) Inflation	
	(c) Interest Charges	
7.4	Process Economics : Economic Analysis	170
A.	Analytical Techniques Employed	170
	(a) Net Present Value (NPV)	
	(b) Internal Rate of Return (IRR)	
	(c) Breakeven and Sensitivity Analysis	
	(d) Investment Simulation	
B.	Results and Discussion	172
	(a) NPV and IRR	
	(b) Breakeven and Sensitivity Analysis	
	(c) Investment Simulation	
C.	Summary of the Implications of the Economic Analysis	184
7.5	Market Potential for Recycled Rubber Manufactured using New Technologies	191
7.6	Compound Cost-Property Relationship of Rubber Vulcanizates Incorporating Recycled Rubber	193
CHAPTER 8	<u>CONCLUSION AND FURTHER RESEARCH OPPORTUNITY</u>	204
8.1	Rubber Supply Situation	204
8.2	Rubber Recycling Procedures	205
	(a) Forms of Input and Output of Recycling Processes	
	(b) Economic Analysis	
	(i) Scrap tyre cost	
	(ii) Price of recycled rubber	
	(iii) Cost of liquid nitrogen	
	(iv) Labour, fixed and capital costs	
8.3	Physical Properties of Recycled Rubber Incorporated Rubber Vulcanizates	212
	(a) Curing Agent Migration	212
	(b) Volume Fraction and Particle Size of Incorporated Rubber Crumb	213
	(c) Coupling between Particles and Filler	216
	(d) Stress-Strain Relationship	217
	<u>REFERENCES AND BIBLIOGRAPHY</u>	220
	<u>APPENDICES</u>	
A.	Survey of Rubber Recycling Facilities in Europe and North America.	
B.	Details of Commercially Available Rubber Recycling Processes.	
C.	Mechanics of Rubbery Materials.	
D.	Mechanics of Composites.	
E.	Experimental Procedure and Results of WTC-SBR and WTC-NR composites.	
F.	Brief Description of Scanning Electron Microscopy.	

continue APPENDICES

- G. Detail Cost Data for ND, KEK-BOC Process.
- H. Investment Appraisal Techniques.
- I. Investment Simulation.

PUBLICATION

1. Influence of the Cure System on the Properties of Vulcanizates
Incorporating Particulate Scrap Rubber, Plastics and Rubber Institute
Annual National Conference on Crosslinking and Network Formation in
Polymers, London, October 1982.

There has been renewed interest in the recycling of crude oil related materials since the advent of the oil price crisis in 1973. These conservation efforts have concentrated on the reduction of overall material inputs and on energy usage. The processing of all rubbers requires a high energy input and synthetic rubbers are derived from a crude oil input. Hence from the conservationists' point of view, recycling of scrap rubber is desirable because of the potential savings in fossil fuel inputs.

Environmental factors also point to the need for recycling this material because the non-biodegradable nature of scrap rubber makes it unsuitable for normal waste disposal procedures such as landfilling, and may cause environmental pollution through improper dumping.

The magnitude of the scrap rubber related problem may be quantified through the amount of scrap rubber discarded each year. Although detail figures are not available, the total amount of scrap rubber and the quantities of discarded rubber articles can be estimated through the rubber consumption and rubber products sales figures. This has been done in Chapter Two. A more accurate estimate for the quantities of scrap vehicle tyres can be obtained from published data on the tyre replacement market sales figure and the number of vehicles scrapped each year (58). By this method of estimation, in the UK some 20 million scrap car and van tyres would have been turned into scrap in 1979. 30% of these scrap tyres were estimated to have been recycled through retreading (45), there were some 13 million scrap tyres left that required proper disposal, and posed an environmental pollution threat. It also provided the rubber recycling industry with an abundant and readily available supply of raw material input. This has been pursued further in Chapter Three.

There have been several recent investigations into the recycling of scrap tyres. The seriousness of the scrap tyre problem is indicated by the setting up of a parliamentary commission for the sole purpose of studying the reclamation and reuse of these scrap tyres (58). This study makes interesting reading and contains a large amount of information and data. However the economics of the recycling processes and technical data on the products of the rubber recycling industry

are not considered. Consequently the usefulness of this document to a party interested in recycling rubber is limited.

A number of options for the reuse of scrap rubber exist (60). These include landfilling, energy recovery through incineration, raw material recovery by pyrolysis, reclamation and comminution. The alternative options available for a particular reclaimed rubber producer, in a situation of declining demand and high cost of manufacture, is the subject of study by Norman (45). Although there are some advantages of associating an investigation with a particular recycled rubber company, this study tended to be rather narrow in its approach, confining itself almost exclusively with the activities of one company. The usefulness of the study is also limited by the lack (or exclusion) of economic data and analysis. The important technical investigation on the physical properties of recycled rubber incorporated rubber compounds was not included also. The understanding of these physical properties is important in establishing new markets for the recycled rubber and establishing confidence among rubber processors in the use of higher proportion of recycled rubber.

The American investigations (62, 69) may form a good basis for the investigation of available rubber recycling technologies, especially for scrap rubber tyres. However, the economic data and analysis were largely presented in a non-compatible market and currency system.

The advent of the 1973 oil price crisis had caused energy prices to increase sharply, which had in turn increased the production cost of rubber reclaimers. Subsequently, with soft demand, resulting from the economic recession of the seventies, many recycled rubber manufacturers employing the conventional high energy input rubber reclaiming process had been forced out of business. This situation was not unique to the UK, but, as the survey of rubber recycling facilities in Europe and America (see Appendix A) indicated, the situation was much the same in Europe and North America. At present (1982) there is only one rubber recycler in the UK.

The scope of the present investigation is restricted to the reuse of scrap rubber as a primary raw material for product manufacture. During the course of the investigation into the rubber recycling industry, it became clear that appropriate recycling process technology already

exists and that the major difficulties are related to the process economics, and the properties and economics of rubber compounds incorporating recycled rubber. Little detailed information on the economics of the majority of commercially operated processes is available. In this work, data has been obtained for the cryogenic grinding of scrap rubber, a technology which seems to have some potential for commercial exploitation, and a thorough economic analysis performed. The analytic methods include traditional Net Present Value (NPV) / Internal Rate of Return (IRR) appraisal, break-even and sensitivity analysis using specially developed expressions to determine the long term break-even conditions, and an investment simulation model based on the NPV of the investment and where the single point variables were replaced by variable probability distributions that represent a more realistic situation. The methods and results of the analysis are presented in Chapter Seven.

Few systematic scientific investigations into the properties of rubber compounds incorporating recycled rubber have been reported. In this project investigation has been carried out using 40 mesh whole tyre rubber crumb as the recycled rubber incorporated into SBR (a general purpose synthetic rubber) and NR (natural rubber) based compounds. An attempt has been made to analyse the small amount of published data together with results from our investigation in terms of the theory of composites eg. Kerner, Gent and Simple Law of Mixtures models, and to establish models which could be used to predict the physical properties of the compounds. These models are needed to establish equations which can be used to analyse unit material cost of vulcanizates incorporating scrap rubber crumb manufacture according to a particular compound specification. An example of this approach is given in Chapter Seven, which includes material property considerations and effect of sulphur curing agent migration. The analysis carried out using Gent model indicates that strength property is related to the effective particle diameter, d_{eff} of the rubber crumb, and it is not necessary to grind the scrap rubber to a diameter of less than 20 μm (see Chapter Five). This has a significant industrial importance in that, although it is desirable to obtain crumb of small particle sizes, comminuting the crumb below 20 μm does not offer additional property enhancement.

The mechanisms governing the physical properties of these recycled

rubber incorporated rubber vulcanizates are also the subject of the investigation. The stress-strain relationships of these rubber composites have been used for this investigation, and analyses using the Mooney-Rivlin and Inverse Langevin material models, which has not been done previously, has led to the identification of the possible mechanisms of failure for these composite materials. The Mooney constants, C_1 and C_2 are also considered. These are detailed in Chapter Five. One critical factor dictating physical properties is the migration of curatives which has been studied using Energy Dispersive Analysis of X-ray (EDAX) technique, the results of which are given in Chapter Six. There was insufficient time for further investigation on other influencing factors.

The implications and results of the economic analysis and material property investigations are discussed in Chapter Eight. It is recognized that the material property investigations carried out in this work have not resolved the problem of material property modelling. However they have resulted in a better understanding of the mechanics involved and indicate areas of future research.

This work has taken a multi-disciplinary approach to the investigation of a highly relevant subject, both from the economic and technological points of view. Since it will be of interest to readers having a wide range of backgrounds, use is made of Appendices to explain briefly the basic principles of the topics considered and the analytic techniques employed.

The thesis emphasises the following aspects : (i) the structure of the rubber processing industry and the role of the recycling sectors ; (ii) property relationships in compounds incorporating scrap rubber crumb, with particular attention to material mechanics ; (iii) the estimation of cure agent distribution (since this has a profound influence on the physical properties of the compound) ; and (iv) the economics of the cryogenic comminution of scrap rubber.

2.1 Structure of Rubber Industry in UK

Figure 2.1 shows schematically the structure of the UK rubber industry. The industry may be divided into four main sectors, namely the raw material supply sector, the rubber processing sector, the rubber recycling sector and the market/consumer sector. The recycling sector is small compared with the others.

The raw material supply sector essentially consists of seven synthetic rubber producers, synthetic rubber and natural rubber importers, and rubber compounding ingredient suppliers. A small amount of reclaimed rubber is also imported, mainly from the Eastern European Bloc. For example in 1980, home production of synthetic rubber was 212,400 tonnes. An additional 134,400 tonnes of synthetic rubber was imported. However, 109,200 tonnes were exported, thus resulting in a net synthetic rubber supply in 1979 of 238,800 tonnes. In the same year, 126,000 tonnes of natural rubber and 2,400 tonnes of reclaimed rubber were also imported. The supply of rubbers is dealt with in more detail in the Section 2.2.

The rubber processing sector consists of several hundreds of establishments & companies, and employs over 100,000 employees. In 1979, this sector had 689 establishments and had a workforce of 107,822(144). It can be divided into two main groups: (i) the large companies with 1000 or more employees; and (ii) small/medium size companies with less than 1000 employees. The large companies comprise of mainly the major tyre manufacturers, such as Dunlop, Goodyear, Pirelli, Avon, Firestone and Michelin, and the large rubber processors such as BTR. Apart from tyres of all descriptions, conveyor beltings, industrial and domestic hoses, and general moulded, extruded and calendered rubber products are the main output. In 1979, this group consisted of 3.3% of the total establishments (23 in number), employed 52.4% of the total workforce and generated about 58% of the gross output⁺.

The small/medium size companies produce a wide diversity of moulded or extruded general rubber goods, mechanical and engineering rubber products such as oil seals. Tyre retreading is also a major activity. The majority of these companies employ less than 100 employees. In 1979, these small companies accounted for 78.1% of the total number of establishments, but employed only about 9.4% of the total workforce,

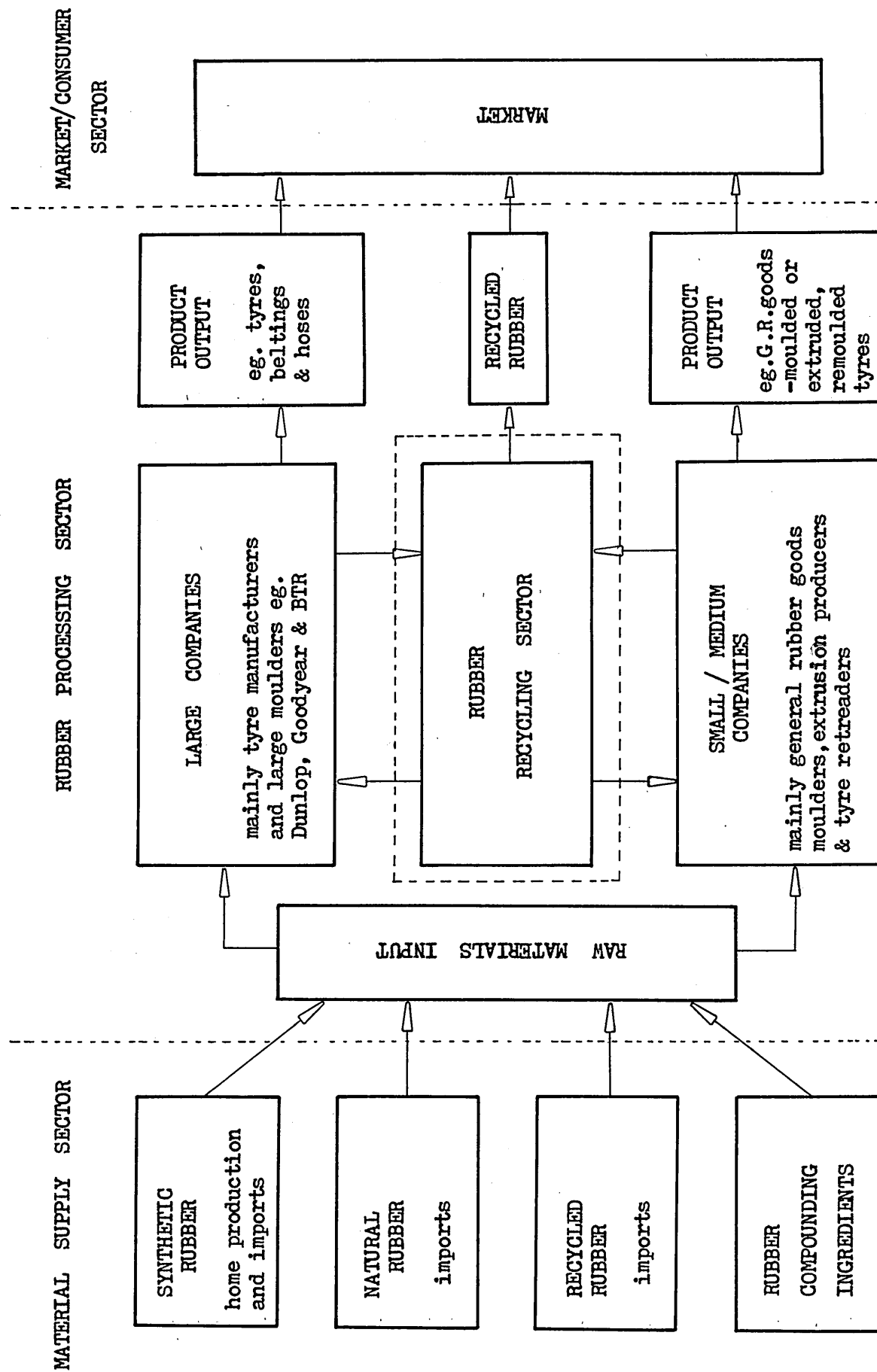


FIGURE 2.1 Structure of Rubber Industry in U.K .

and generated slightly less than 8% of the gross output⁺. The medium size companies (each employed between 100 to 1000 employees) comprised of about 19% of the total establishments, employed about 38% of total workforce in the rubber processing sector and were responsible for about 34% of the gross output⁺.

The rubber recycling sector is shown in more detail in Figure 2.2. The flows of inputs and outputs, apart from rubber for recycling or recycled rubber, are not shown for the rubber processing companies. Referring to Figure 2.2, it is seen that three types of rubber recycling facilities can be identified:

(i) In-house recycling. This is mostly carried out by the small/medium size companies where the factory scrap (vulcanized and unvulcanizes) is masticated and reincorporated into its parent compounds. The quantity is usually small, and compounds recycled are usually based on more expensive specialty rubbers such as silicone and fluorocarbon rubbers.

(ii) Recycling facility which is a subsidiary or part of a large company. The facility is to ensure the parent company a secure and steady supply of raw material. United Reclaim Ltd. was one such operation (ceased operation in 1981). Excess output from such facility is often sold on the open market. The other two operations of this type are the Uniroyal Ltd and G. Hughes Ltd.

(iii) Independent recycling facilities. These are usually independent companies, producing recycled rubber, usually rubber crumb, as their main product. At present, this type of rubber recycler is not very successful. None of the facilities (two in total) is currently in operation.

In addition to these three types of rubber recycling facility, the tyre retreading companies also produce tyre tread buffings and rubber crumb as a by-product. These can be used as a recycled rubber or as a material input into some rubber recycling processes.

The market for recycled rubber is one of the areas where further investigative is needed.

(⁺ gross output includes total sales, work done, work in progress and goods on hand for sale.)

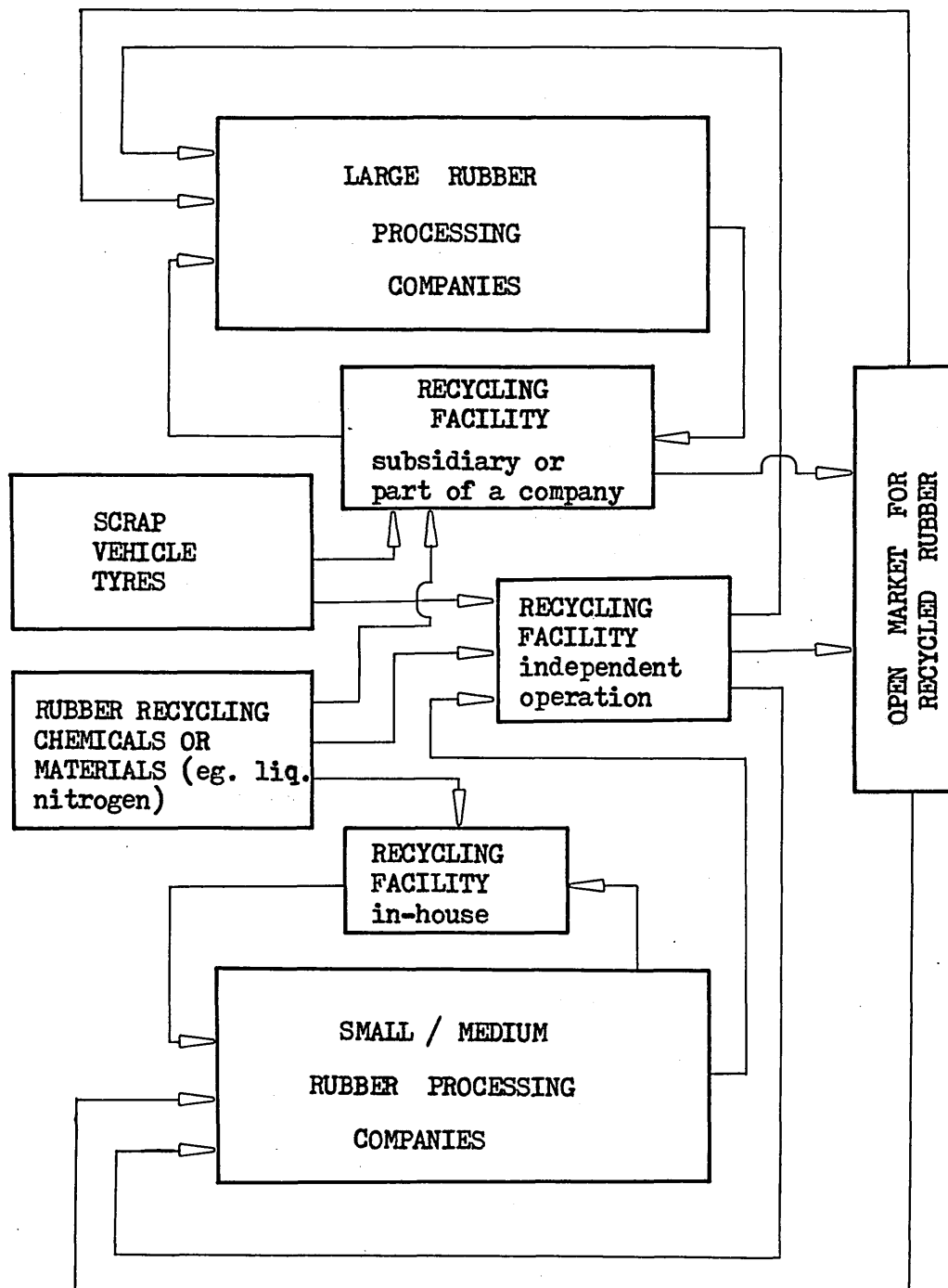


FIGURE 2.2 Rubber Recycling Sector

Referring back to Figure 2.1, the market/consumer sector is dealt with in more detail in section 2.3. It should be noted that the main rubber product, tyres, has been facing a declining market - resulting from high petrol cost, less new car sales and longer lasting tyres (radials).

2.2 Sources, Forms and Supply of Rubber

(a) Sources and Forms

Rubbers can be classified into two general ways, namely Tree Rubbers and Synthetic Rubbers. These two broad categories can again be divided into groups according either to their origins or to their chemical nature. Tree rubbers tend to be named by their origins whilst synthetic rubbers are usually named after their chemical constituents.

Natural Rubber, known botanically as *Hevea Braziliensis*, is probably the most well-known tree rubber. It is also possibly the earliest rubber known to Europeans. Natural Rubber is by no means the only naturally occurring rubber; in fact a great many trees and shrubs also produce rubber. The Guayule rubber obtained from a type of Mexican shrub, *Gutta Percha* and *Balata* are some of the examples.

With the exception of Natural Rubber, tree rubbers have not been cultivated, produced and used in any significant quantity. Quality-wise, the Natural Rubber is far superior to the other tree rubbers which usually have a high resin content. Natural Rubber has managed to maintain its competitive edge through a carefully planned research and development scheme. Guayule rubber is under serious study (167), and commercial exploitation is expected in the light of limited petroleum resources and rising crude oil prices. Other tree rubbers are also exploited, such as the rubber-bearing dandelion of Russia and the Jelutong tree of the Malay Peninsula.

Natural rubber was originally supplied in the form of ribbed smoked sheets of about 5 mm thickness, containing high percentage of impurities such as dirt. Nowadays, natural rubber can be obtained in a wide variety of forms such as bales, sheets, pellets and powder. Technically specified natural rubbers which have controlled viscosities and dirt contents such as SMR CV 50 (Standard Malaysian Rubber with a maximum of 0.03% by weight of dirt and a Mooney viscosity of 50 ± 5) is gaining popularity among the rubber processors. Oil extended and carbon black master batches of natural rubber are also available.

With successful pyrolysis of natural rubber, the base unit of natural rubber was identified. This had led to the invention and development of the synthetic rubbers. The large-scale production of the early synthetic rubbers was closely associated with the Second World War.

Prior to the World War, almost all the rubber used was natural rubber. With the advent of war, natural rubber supply from Brazil and the Far East was cut off due to difficulty in transportation. Mass transport for the armed forces requires increasing amounts of rubber tyres and therefore demand for rubber increased. This desperate situation led to the expansion of the development and production of the BUNA-S rubber in Germany, while on the other side of the Atlantic Ocean the United States of America was building more GR-S rubber plants to cope with the increased demand. The reclaimed rubber industry also flourished. Both the BUNA-S and GR-S rubberd are copolymers of styrene and butadiene, polymerised under different catalysts and conditions.

Styrene-Butadiene copolymers, or perhaps more widely known as Styrene-Butadiene Rubbers (SBR), is only one member of the synthetic rubber group. However, SBR is by far the largest tonnage consumed of general purpose synthetic rubber. The SBR poses a competitive threat to Natural Rubber in general purpose applications. Price stability has been an advantage of SBR over NR. The availability of SBR in various grades, and grades according to customers' requirements such as oil-extended and carbon black master-batches, makes SBR more attractive and competitive.

Apart from SBR, there are a great number of other specialised synthetic rubbers. These specialised synthetic rubbers are usually produced according to service requirements. Polychloroprene, or better known as Neoprene, and nitrile rubbers are general purpose oil resistant rubbers. For extreme temperatures of applications, silicone and fluoro-carbonated rubbers are being developed. These tailormade rubbers can be obtained in many grades according to the service conditions. The quantities of specialised rubbers used are comparatively small and their costs are high (see for example Figure 2.5).

Currently, there are seven synthetic rubber producers in the UK, having a total output capacity of 530,000 tonnes (per year), and producing a wide range of synthetic rubbers and lattices such as SBR, Nitrile, Polychloroprene, Butyl and Chlorobutyl, Polubutadiene and EPDM (a copolymer of ethylene and propylene) (166). SBR has the highest capacity of 55% of the total. The home supply of synthetic rubber, as illustrated in Section 2.1 above, consists of home production and imports with exports deducted. The imports are mainly specialty rubbers such as

fluorocarbon and silicone rubbers. The SBR can be obtained in a wide range of grades and may be in the form of bales, slabs, pellets or powder. Premixed master batches are particularly popular with silicone rubbers.

(b) Supply and Consumption

The home supply, consumption and stock of rubbers are monitored monthly by Business Monitor (144), PM491, and Rubber Statistical Bulletin (164). The quarter's performance of the rubber processing industry is summarised in a Business Monitor quarterly publication (PQ 491). An annual census (PA 491) is also published. The figures given by Business Monitor and Rubber Statistical Bulletin were slightly different due possibly to the exclusion or inclusion of some sources. The discrepancy was about 3 to 5%. For the purpose of consistency, the figures quoted by Business Monitor are used. It is more comprehensive and reliable.

Table 2.1, 2.2 and 2.3 summarise respectively the rubber supply, consumption and stock to the UK as compiled by the Business Monitor.

Figure 2.3 shows graphically the supply and consumption (demand) trends of natural, synthetic and reclaimed rubbers in the UK market.

The rubber supply figures include the import figures but the export figures were deducted. Therefore, an increase in net home (UK) supply can arise from:

- (a) an increase in home production;
- (b) an increase in import;
- and (c) a decrease in export,

or a combination of the three. For a closer analysis of each of these on the net home supply of rubber, detailed figures of home productions, imports and exports must be taken into account. These detailed figures can be obtained from the monthly issues of the refereces (144, 164) cited above.

With reference to Figure 2.3, the supply of synthetic rubber shows a general increasing trend until late 1970's. A closer examination of the statistics suggests that this increasing supply trend is due to increasing home production, increasing imports coupled with a roughly constant, if not a small fluctuating export figure. Between 1979 and 1980, the synthetic rubber supply fell dramatically to 1969 level of

Table 2.1 Rubber Supply in the UK

Figures in Thousand Tonnes

Year	Natural Rubber	Synthetic Rubber	Total New Rubber (NR + SR)	Reclaimed Rubber			Grand Total	% Reclaimed Rubber	% New Rubber
				Import	Production	Export			
67	184.8	218.4	403.2	1.2	32.4	6.0	432.0	6.4	93.3
68	194.4	241.2	435.6	1.2	34.8	8.4	462.0	5.7	94.3
69	198.0	262.8	460.8	1.2	33.6	8.4	488.4	5.4	94.3
70	194.4	282.0	476.4	-	28.8	7.2	499.2	4.3	95.4
71	188.4	258.0	446.4	1.2	28.8	6.0	471.6	5.1	94.7
72	171.6	271.2	442.8	1.2	25.2	6.0	463.2	4.4	95.6
73	187.2	324.0	511.2	1.2	26.4	8.4	530.4	3.6	96.4
74	162.0	282.0	444.0	1.2	26.4	9.6	463.2	4.1	95.9
75	169.2	266.4	435.6	1.2	24.0	7.2	452.4	4.0	96.3
76	171.6	324.0	495.6	1.2	24.0	9.6	512.4	3.0	96.7
77	168.0	321.6	489.6	2.4	22.8	8.4	506.4	3.3	96.7
78	138.0	312.0	450.0	2.4	20.4	6.0	466.8	3.6	96.4
79	133.2	307.2	440.4	3.6	19.2	7.2	456.0	3.4	96.6
80	126.0	238.8	364.8	2.4	15.6	7.2	376.8	2.9	97.1

Table 2.2 Rubber Consumption in the UK

Figures in Thousand Tonnes

Year	Natural Rubber	Synthetic Rubber	Total New Rubber (NR + SR)	Reclaimed Rubber		Grand Total	% Reclaimed Rubber	% New Rubber
				Tyre & Tyre Product	Non-Tyre Products			
67	170.4	188.4	358.8	-	-	27.6	7.1	92.6
68	186.0	218.2	404.2	-	-	27.6	6.4	93.6
69	181.2	238.8	420.0	-	-	24.0	5.4	94.6
70	177.6	256.8	434.4	-	-	21.6	4.7	95.0
71	176.4	260.4	436.8	-	-	20.4	4.4	95.0
72	164.4	255.6	420.0	-	-	19.2	4.4	95.9
73	162.0	264.0	426.0	9.6	8.4	18.0	(3.4) 4.1	(79.4) 95.9
74	157.2	255.6	412.8	8.4	9.6	18.0	3.9	88.7
75	157.2	222.0	379.2	8.4	9.6	16.8	3.7	83.2
76	159.6	259.2	418.8	8.4	8.4	16.8	3.3	82.3
77	156.0	265.2	421.2	8.4	7.2	15.6	3.1	82.4
78	133.2	234.0	367.2	7.2	7.2	14.4	3.1	78.5
79	132.0	256.6	357.6	6.0	6.0	12.0	2.6	78.6
80	124.8	201.6	326.4	4.8	6.0	12.0	3.1	83.2

Table 2.3 Rubber Stock in the UK

Figures in Thousand Tonnes

Year	Natural Rubber	Synthetic Rubber	Total NR + SR	Reclaimed Rubber	Grand Total	% Reclaimed Rubber	% New Rubber
67	288.0	405.6	693.6	43.2	738.0	5.9	94.0
68	279.6	457.2	736.8	36.0	772.8	4.7	95.3
69	320.4	606.0	926.4	45.6	972.0	4.7	95.3
70	310.8	778.8	1089.6	26.4	1117.2	2.4	97.5
71	357.6	688.8	1046.4	39.6	1080.0	3.7	96.0
72	328.8	709.2	1038.0	37.2	1077.6	3.5	96.3
73	342.0	638.4	980.4	22.8	1003.2	2.3	97.7
74	276.0	676.0	952.8	27.8	980.4	2.8	97.2
75	290.4	684.0	974.4	24.0	998.4	2.4	97.6
76	374.4	657.0	1032.0	26.4	1058.4	2.5	97.5
77	344.4	669.6	1014.0	24.0	1038.0	2.3	97.7
78	348.0	662.4	1010.4	33.6	1044.0	3.2	96.8
79	331.2	726.0	1057.2	42.0	1099.2	3.8	96.2
80	256.8	532.8	789.6	16.8	806.4	2.1	97.9

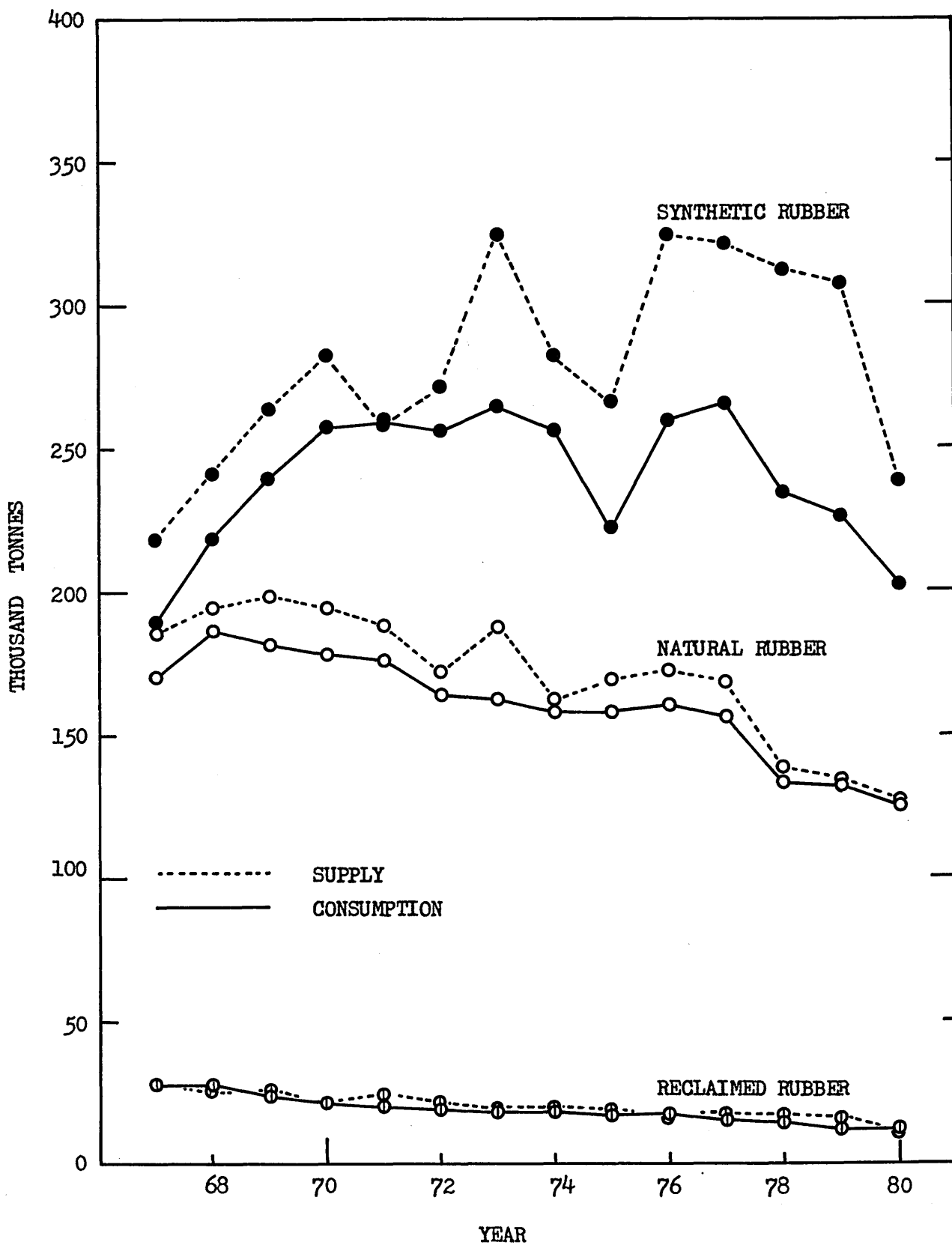


FIGURE 2.3 Supply and Consumption of Natural, Synthetic and Reclaimed Rubbers

about 240,000 tonnes. This was due to an almost 25% reduction in home production and a decreased import.

It is interesting to see that there was no apparent time lag in fulfilling the fluctuating consumption (demand). This might indicate that the synthetic rubber plants were operating below their optimum capacity. The consumption of synthetic rubber in the UK in recent years was in the region of 250,000 tonnes, and the synthetic rubber plants were operating in the region of 45-50% capacity.

The impact of the oil crisis of the early 1970's shows in the graphs. The recovery from this crisis is clearly shown over the 1975-76 period with home supply of synthetic rubber reaching a peak of 324,000 tonnes, while consumption increased from the low 222,000 tonnes in 1975 to 259,000 tonnes in 1976.

The increasing trend of synthetic rubber supply and consumption could be at the expense of its natural counterpart. Both the supply and consumption figures for natural rubber show a falling trend. The consumption of natural rubber declined at a steady rate over the period from the late 1960's to 1980, averaging at about 3,400 tonnes per year. The supply figures fluctuated more vigorously, especially during the mid 70's. The volatility of natural rubber price could have caused such behaviour. Again the supply was very sensitive to demand, responding to it without any apparent time lag. The UK import of natural rubber had fallen by one third from the 1969 level of 198,000 tonnes to 126,000 tonnes in 1980.

Reclaimed rubber has a very gloomy outlook. The supply of reclaimed rubber has been falling at a rate of roughly 1000 tonnes per year over the period covered. In 1980, the net home supply of reclaimed rubber was 10,800 tonnes. With the recent closure of one of the two reclaimed rubber plants in UK, it is doubtful if the supply could stay at this level. The consumption of reclaimed rubber has also been falling in line with supply. It did not show any sign of recovery after a slower rate of decline during the period 1973 to 1976. Note that this period coincides with the advent of the oil price crisis. The selling price of reclaimed rubber compared with that of virgin rubbers (see Section 2.4), and the imparted inferior physical properties when using

reclaimed rubber (see Chapter 5 and Appendix D), may have contributed to the declining reclaimed rubber market.

(c) Stock

Figure 2.4 shows the stocks of natural, synthetic and reclaimed rubbers graphically. It can be seen that synthetic rubber built up a large quantity of stock towards the end of the 1960's. It then slowly drifted down to a level of about 670,000 tonnes throughout the 1970's, but dropped drastically to about 530,000 tonnes in 1980.

The stock trend of natural rubber in the UK is more irregular. This is probably because natural rubber is bought (or imported) from overseas markets rather than produced at home in capital intensive plants, where fluctuation in output is highly undesirable. The stock increased fairly rapidly over the end of the 1960's and early 1970's, reaching 358,000 tonnes in 1971. It then decreased to a low level of 276,000 tonnes in 1974 before increased to a peak of about 374,400 tonnes in 1976. From then the stock figures fell quite rapidly to the lowest level of about 257,000 tonnes in 1980.

It should be noted that the stock of synthetic rubber was about two times as much as that of natural rubber over the period covered.

Reclaimed rubber stock was very low compared with synthetic and natural rubbers, in the region of 30,000 to 40,000 tonnes. It fluctuated up and down, but showed a general decreasing trend.

2.3 Rubber Consumption by Product

The detail consumption figures of rubber by product are not easily available from published statistics. However, the trends of the consumption of rubber by various rubber products can justifiably be estimated by the sale trends of these rubber products. The sales of rubber products by UK manufacturers are monitored by the quarterly issues of the Business Monitor (144), PQ 491. The sales figures for the main rubber products, for example, tyres, tubes, hose and tubing, belting and sheeting, are extracted from Business Monitor and tabulated in Table 2.4

Tyre and tyre products (eg. tubes and tyre repair patchings) consumed

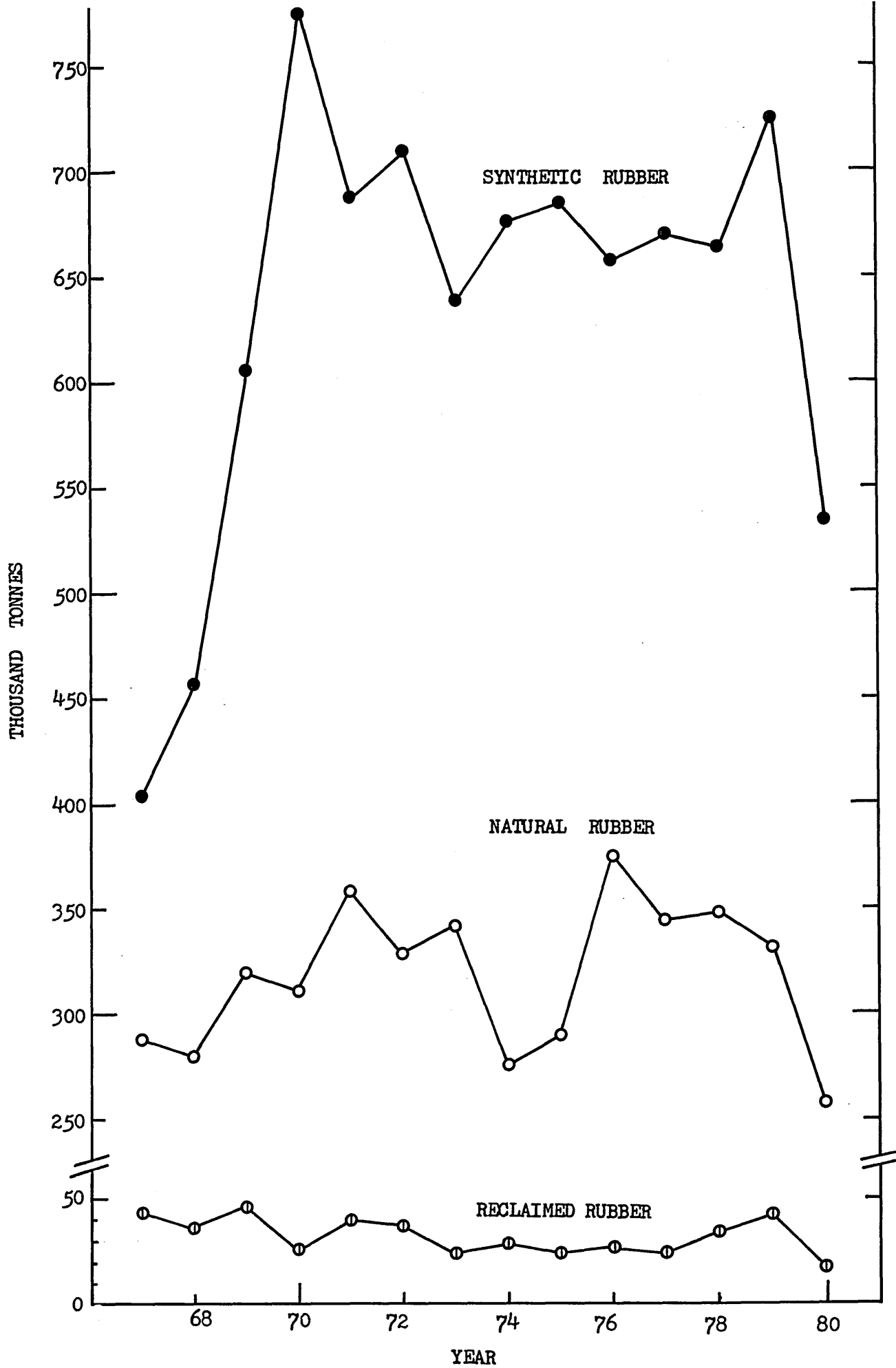


FIGURE 2.4 Rubber Stock - 19 -

Table 2.4 Sales of Rubber Products in the UK

Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Units	000's	000's	000's	000's	000's	000's	000's	000's	000's	tonnes	000's	000's	000's	Th m	tonnes
1971	13,461	10,274	3,510	1,011	7,544	NA	5,016	2,474	715	NA	NA	NA	NA	11,912	13,701
2	13,028	14,813	3,701	1,084	7,270	936	5,190	2,482	729	NA	NA	NA	7,518	11,310	12,661
3	9,528	17,125	3,798	1,144	6,947	1,110	4,694	2,641	835	NA	NA	NA	9,035	12,851	13,712
4	7,592	16,675	3,575	1,116	5,356	983	3,830	2,448	800	NA	NA	NA	6,892	12,588	15,377
5	6,172	17,527	3,532	1,040	4,822	918	4,508	2,492	777	19,196	11,084	7,882	8,091	11,691	12,614
6	5,274	20,156	4,227	1,107	4,784	921	5,068	2,868	846	16,972	10,678	7,910	6,196	14,184	13,840
7	4,095	19,920	3,863	1,179	4,978	838	4,727	2,659	900	19,693	10,428	8,909	8,196	14,418	16,420
8	3,646	21,198	3,550	908	4,796	859	5,431	2,747	788	15,050	9,349	8,609	8,897	15,773	15,412
9	2,994	21,204	3,715	883	3,326	NA	5,182	2,720	837	18,493	8,899	9,889	8,576	15,300	17,712
1980	2,095	22,548	3,421	598	NA	596	4,984	2,622	NA	14,910	7,583	8,224	NA	13,554	14,919

KEY

NA = Not Available

Th m = thousand metres

Number SALES OF

- 1 Tyres (new covers), passenger cars and vans, Cross-plied.
- 2 Tyres (new covers), passenger cars and vans, Radial-plied.
- 3 Tyres (new covers), commercial vehicles.
- 4 Tyres (new covers), tractors.
- 5 Retreaded tyres, cars and vans.
- 6 Retreaded tyres, commercial vehicles.
- 7 Tubes, cars and vans.
- 8 Tubes, commercial vehicles.
- 9 Tubes, tractors, earthmovers and land / road.
- 10 Belting, conveyor and elevator belting (including solid woven, coated or impregnated with rubber).
- 11 Belting, transmission belting, motor vehicle fan belt.
- 12 Belting, transmission belting, industrial V-belt.
- 13 Belting, transmission belting, belts for domestic appliances.
- 14 Hose and tubing, unreinforced rubber hose and tubing.
- 15 Sheets, unsupported sheeting of natural or synthetic rubbers.

about 45% of the total rubber consumption (164), of which about 60% is synthetic. However, as the cross-ply tyres are gradually replaced by the radial-ply tyres, more natural rubber would have to be used (for technical considerations). The move from cross-ply tyres to radial-ply tyres is clearly seen from the data (see Table 2.4). The sales of cross-ply tyres fell from about 13.5 million units in 1971 to a mere 2.1 million in 1980, whilst radial-ply tyre sales have more than doubled over the same period. A sales figure for radial-ply tyres of about 22.5 million units was recorded in 1980. In spite of the falling sales of cross-ply tyres due to the move to radials, the total number of passenger car and van tyres sold has shown a general trend which is in agreement with that of rubber consumption figures (as shown in Figure 2.3), fluctuating with it. The commercial vehicle tyres, however, have not shown this continuous trend. After increasing during the period 1971-76, the sales have more recently shown a decrease, reaching a lowest level of slightly more than 3.4 million units in 1980. This may be due to the effect of decreasing demand for these tyres in the home market because of a decline in the production of commercial vehicles and in the replacement market. The fact that the average weight of a truck tyre is about six times that of an average passenger car/van tyre, amplified the effect of the relatively small reduction in the sales of commercial vehicle tyres. For instance, over the 1979-80 period, there was a drop in the sales of commercial vehicle tyres of about 300,000 units. This is equivalent to a reduction of sales of some 1,800,000 units of passenger car/van tyres in terms of the weight of rubber consumed. The same argument can be applied to the sales of tractor tyres which would carry a bigger amplifying factor. The sales of tractor tyres were quite constant through the 1970's but shows a drastic reduction towards the end of the 1970's.

To sum up the observation made regarding the consumption of rubber by the tyre industry, the increase in rubber consumption resulting from increasing sales of radial-ply tyres may have been offset by the decrease in rubber consumption resulting from declining sales of cross-ply tyres, commercial vehicle tyres and tractor tyres. Such offset in consumption is confirmed by the decreasing trend of rubber consumption shown in Figure 2.3. The effect of higher petrol cost may be one possible cause of a lower rate of new car sales and less mileage travelled, therefore less tyres were consumed or replaced. The increase in average service life of a tyre as a result of the popularity of high

mileage radial-ply tyres, is another major cause of the decrease in tyre sales.

The situation concerning the tyre retreading industry was much the same. Sales of retreaded car and van tyres fell from about 7.5 million units in 1971 to the recent average of about 4.8 million units. This average sales figure seemed to have held for several years, from 1975 until 1978. A large drop in sales to about 3.3 million units is observed over the 1978-79 period, breaking the steady trend. In the commercial vehicle tyre retreads, a slight recovery in sales performance is observed in 1978, after a continuous slow drop in sales since 1973. Again a drastic sales reduction is observed towards the end of the 1970's.

Tyre tubes have not been able to hold up their sales. This is mainly due to the increasing popularity of tubeless tyres especially the tubeless radials. In the belting sector, conveyor and elevator belting showed a wild fluctuation of the amplitude of about 3,000 tonnes, while motorcar fan belts sales had been declining. Hose and tubing made wholly from rubber enjoyed increasing sales.

The general outlook for the rubber product manufacturing industries in the UK, judging from the sales figures is bleak if the trend observed above continues or demand stabilises at its current level. Consequently, it may be assumed that the consumption of rubber in the UK is not likely to increase over the coming years, more probably the decreasing trend will persist.

2.4 Historical Review of Rubber, Petroleum and Energy Costs

(a) Rubber Prices (164, 165)

Figure 2.5 shows the price movements of natural and synthetic rubbers over the 1970's. Prices for two grades of SBR (general purpose) and two specialty rubbers (butyl and nitrile) are shown together with that for natural rubber (RSS 1 London spot price).

It can be seen that the synthetic rubbers followed a similar increasing trend. After a relatively moderate increase through the early 70's, the synthetic rubber prices showed a sudden rise in 1973, then followed by a slightly less rapid increase through to 1980. This sudden rise in price coincides with the crude oil price crisis of 1973 as shown in Figure 2.6. In fact, the price trend of synthetic rubbers followed

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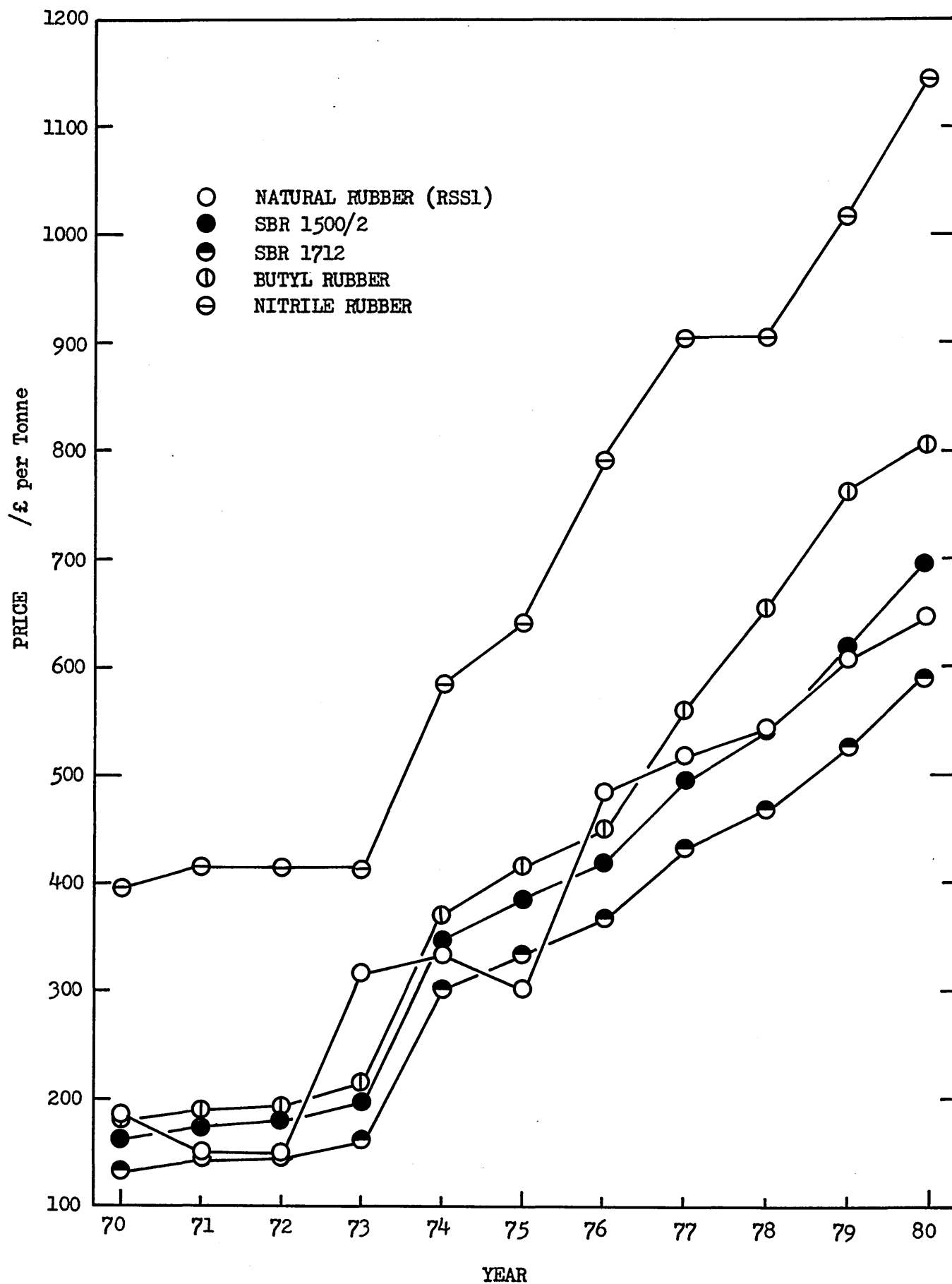


FIGURE 2.5 Price Movement of Natural and Synthetic Rubbers

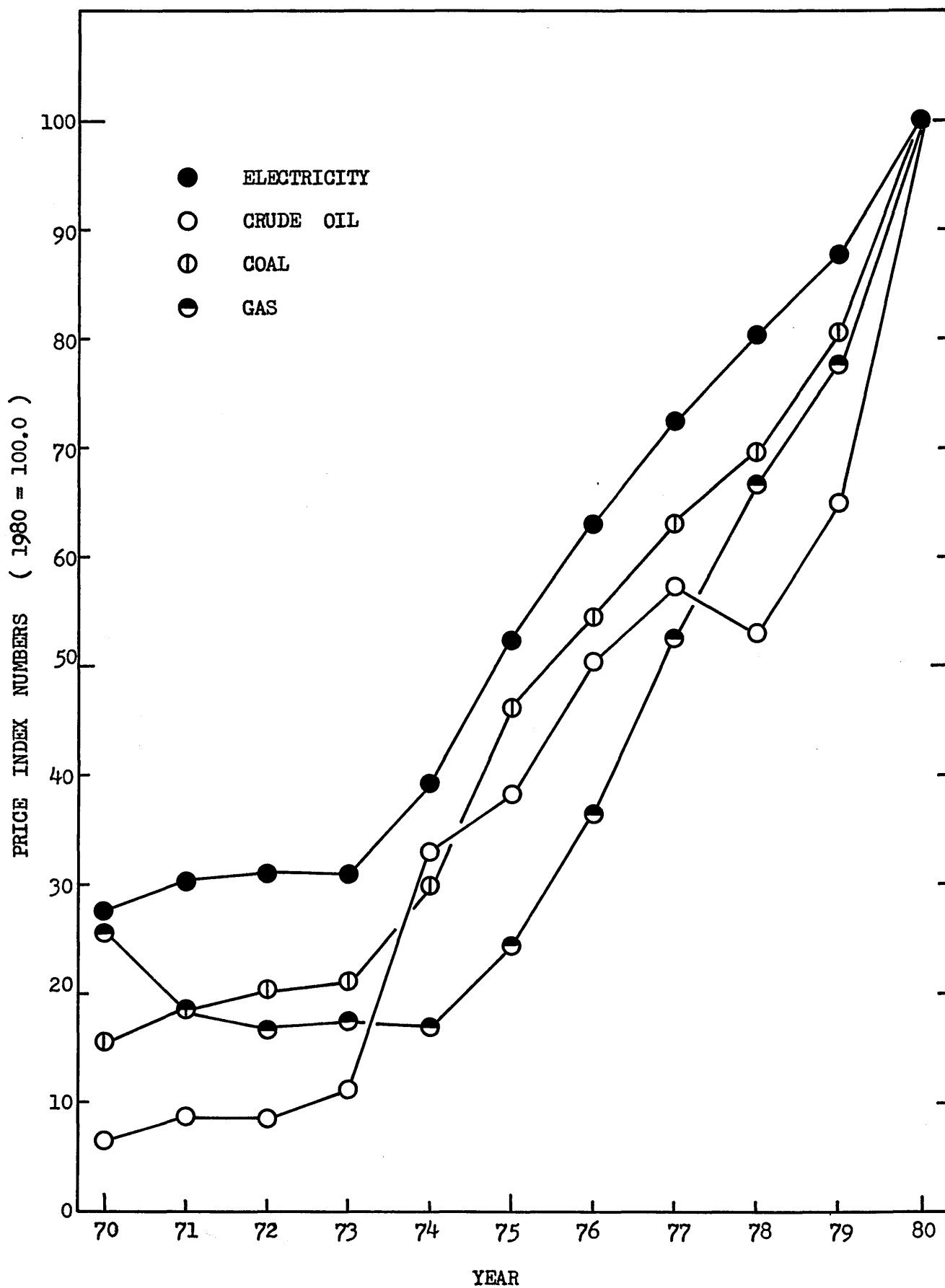


FIGURE 2.6 Index Numbers of Prices of Fuels Used by Industry

quite closely to the general trend of crude oil prices over the period studied. This is because as crude oil price increases, it brings up the price of synthetic oil, and consequently the prices of synthetic oil based products such as synthetic rubbers and carbon black (a vital ingredient for rubber compounding). It should also be noted that oil resistant nitrile rubber (cold polymerisation with medium acrylonitrile content of about 30%) costs about twice as much as the general purpose SBR.

The natural rubber prices were less stable. It fluctuated more vigorously. After decreasing to a low price level of about £150 per tonne in 1972, lower than SBR 1500/2, natural rubber price shot up to £315 per tonne in 1973, more than doubled its 1972 price level. It then passed through the £330 mark (in 1974) before settling down to a lower price of £302 in 1975. In 1975, the natural rubber price was the lowest among the rubbers studied, about £35 per tonne lower than the oil extended grade of SBR (SBR 1712). Natural rubber price then took a sharp upturn and increased to the similar levels as SBR 1500/2 in the late 70's.

Whereas synthetic rubber price trends can be quite confidently predicted from the price of movement of the crude oil natural rubber price is less predictable as the factors influencing its price are more complex. It may depend on the yield of the rubber trees of that particular year, which in turn depends on several elements such as the climatic conditions.

One of the purposes of the natural rubber buffer stock held by the USA is to dampen the wild fluctuations in natural rubber price. Whether it has succeeded in doing so is debatable. In addition, price will be influenced by the sterling exchange rate and the transport costs, both of which will tend to have adverse effect on natural rubber price.

(b) Recycled Rubber Prices (122)

The price movements of recycled rubbers through the 1970's are presented in Figure 2.7. Price trend of recycled rubber crumb for the near future is discussed in Section 7.3.

The prices for all three recycled rubbers i.e. whole tyre reclaim, 30 mesh and 40 mesh rubber crumb, showed a consistent increase throughout the period considered. The effect of the oil price crisis showed more

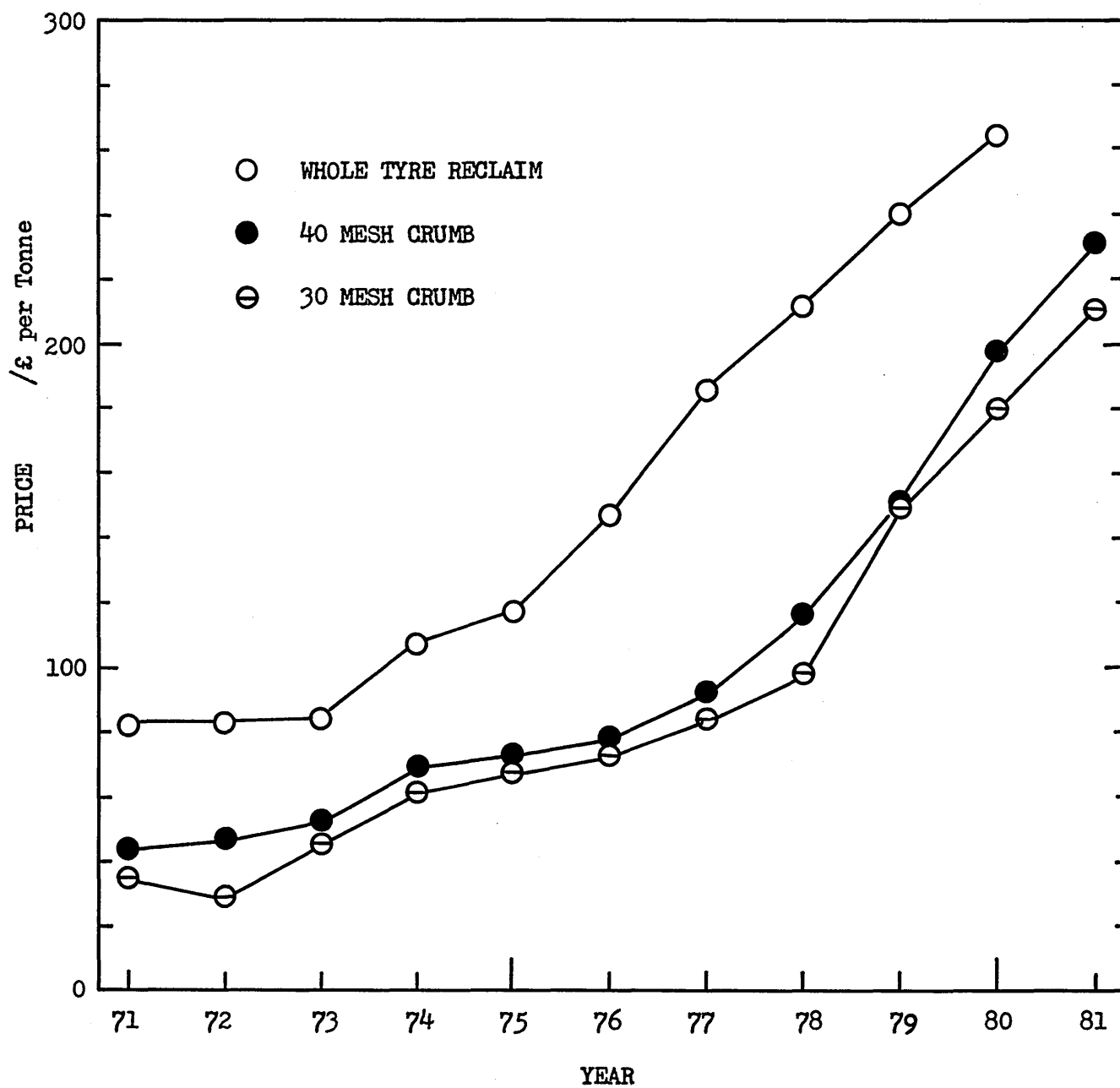


FIGURE 2.7 Price Movement of Recycled Rubbers

profoundly with reclaimed rubber than with rubber crumb. The sudden up surge in oil price in 1973 had pushed up the energy costs, especially electricity (see Figure 2.6). Being a high energy consuming industry, especially in the reclaimed rubber sector, rubber recycling manufacturers faced a sudden increase in the cost of process energy input. This added energy cost had passed on to the consumer through the recycled rubber price.

Most conventional rubber recycling processes such as the Reclaimator and Digester (see Appendix B for a more detail description of the processes) rely heavily on electrical power as their energy input, In fact the Reclaimator process relies solely on electricity. (Energy requires to crack, separate and grind the input whole tyres, and to supply the heat for devulcanization). Hence, increase in energy costs would directly affect the cost of recycled rubber production, and its selling price.

It can be seen that rubber crumb price increased by about $3\frac{1}{2}$ times over the period studied, and whole tyre reclaim price had increased by $2\frac{1}{2}$ times during the same period.

(c) Petroleum and Energy Costs

Figure 2.6 shows the price movements of the energy and fuel used by UK industry. The crude oil prices are also included.

The effects of energy costs in relation to rubber and recycled rubber prices have been discussed in (a) and (b) above. Summarising briefly it can be stated that an increase in energy costs, especially crude oil, will have an adverse effect on the rubber and recycled rubber prices.

3.1 Historical Review of the Scrap Rubber Industry

(a) Forms and Sources

In the early days of rubber recycling, the main sources of scrap rubber were rubber boots and shoes, fire hoses, bicycle tyres, solid truck tyres, matting, shoe soles and heels, horse shoe pad and airbrake hose, as these were the earliest rubber products. As the automobile industry began to grow, tyres and tubes gradually became the main sources of scrap rubber hydrocarbon. These early tyres and tubes were graded mostly by their colour and tread design, which were identifiable by their manufacturers. Some commonly used classifications were Guaranteed, Nobby Tread, Red Top Tyres and off Whites (46). At this time, carbon black had not been used as a reinforcing filler, and white silicates were presumably used in place, therefore the tyres and tubes were of interesting colours and could be identified in this way.

The sorting situation was quite simple and straight forward as the one and only rubber available to the market at that time was natural rubber. A skilled labourer of that time required only to recognise the manufacturer by the colour and tread pattern of the scrap rubber and tyres. Today, with the introduction of specialty rubbers, each of which has several grades, the task of sorting the scrap rubber becomes an elaborate exercise. (However, the criteria for sorting, especially scrap tyres, are different, based mainly on the type of reinforcement in the scrap tyres eg. textile, and steel reinforced tyres).

A consequence of automobile tyres and tubes being the main sources of scrap rubber for the rubber reclaimers was that the task of collecting scrap tyres and tubes by rubber dealers/merchants was slowly taken over by the tyre dealers/merchants. The tyre merchants purchased tyres from tyre manufacturers, both perfects and rejects, or they might buy scrap tyres from tyre dealers. After sorting out the retreadable carcasses (a term used to describe tyre casings) from the scrap tyres, the remainder of the tyres, together with the rejects from the tyre manufacturers were sold to rubber reclaimers at a very moderate price. This is because these tyres were actually a by-product of their main business. Splitters who produced rubber link mats, automobile body shim, and similar products from scrap tyres, were the competitors for scrap tyres. However, as the automobile population increased rapidly, there was no shortage of supply of scrap tyres.

The scrap tyre dealers/merchants and rubber reclaimers contributed positively towards ensuring an adequate rubber supply during the last World War, especially in the United States of America. After the supply routes of natural rubber were cut off, and due to the lack of synthetic rubber production capability, the supply of rubber became acute. The USA reacted with the setting up of a rubber reserve coupled with a scrap rubber collection drive. This drive was extremely successful and 1,200,000 tons was collected with the help of the rubber and tyre merchants, and was sorted and converted by the rubber reclaimers to reclaimed rubber.

The Second World War demonstrated the vulnerability supply of natural rubber and the need for synthetic rubber development. After the War, both America and Britian expanded their synthetic rubber, especially the Styrene-Butadiene Copolymers (better known in America as GR-S or Government Rubber - Styrene) production facilities. The American Government also set up a natural rubber buffer stock for strategic purposes. The advent of the development of various types and grades of synthetic rubber posed a challenge to the tyre merchants and rubber reclaimers alike. New techniques of reclaiming synthetic rubbers were invented which solved the problem of the rubber reclaimers. However, the sorting out of the scrap tyres remained a problem.

The introduction of specialty synthetic rubbers such as Polychloroprene (CR), Butyl, Nitrile (NBR), Silicone and Fluorocarbon rubbers made the reclaimed rubber situation more complicated. This complication, coupled with the lack of suitable technology, increasing energy costs (the rubber recycling processes have high energy input requirements), and the high transport and labour costs, led to the rubber reclaimers' loss of interest in these relatively small quantities of specialised rubbers. Tyres and tubes, being most readily available and having a well organised chain of collection scheme became the main input of the rubber recycling industry.

(b) Rubber Recycling Processes

Patents for new rubber recycling processes have appeared regularly in the patent literature (a list of recycled rubber related patents is included in the Reference and Bibliography section, 74 through 116). This has probably been a natural response to the challenge imposed by the increasing sophistication of rubber products and the urge to refine

the end-products of the rubber recycling processes.

A comprehensive survey of the patented processes from the beginning of the rubber industry in the mid-nineteenth century through to 1955 was carried out by Winkelmann and Ball (70). They made a list of the chronological highlights of the reclaimed rubber related events as recorded in published literature. The search performed was very thorough, covering all aspects of scrap rubber from the sources of information, recycling processes to the evaluation of the reclaimed rubber.

Several of the present-day patent claims have been evolved from earlier obsolete patents, with considerable refinement in technique, improvement in instrumentation, higher degree of controllability and higher efficiency. For example, a 'High Frequency Heating Process' which was granted a French patent in 1947, described a process in which the scrap rubber is placed between two metal plate electrodes connected to the terminals of a high frequency generator. In 1951, another French patent was issued on an essentially similar but slightly improved process. With the advancement in science, technology and engineering, the high frequency generator is replaced by a microwave generator and a process utilising microwave to reclaim rubber was patented by Goodyear Tire and Rubber Company recently (84). The United States patent US 4 049 588 (1977) (109) and US 4 046 834 (1977) (108) issued to Gould Incorporation is a similar case, except that the process concerned is the 'Plasticisation Process'.

With the exceptions of a few of the more recent innovations/inventions such as the cryogenic rubber grinding process (see for example References 77, 86, 90, 95, 107 and 116), most of the recycling processes in commercial usage today were invented in the early half of the twentieth century; the most recent of which is the 'Reclaimator Process'. The first patent was granted in 1953 (128, see also 129). The Reclaimator Process is still being used commercially. The other popular recycling process, the Alkali Process, was patented by A.H. Marks in 1899. A variation of the famous patented process which was described as 'probably the most important reclaiming patent even issued' (70) is still in use in Britain.

Many more patents for scrap recycling processes have since been granted. The process which aroused the most recent interest is the cryogenic

rubber grinding process (see examples given in Appendix B). Cryogenic grinding is not a new invention but the adaptation of such a process to pulverise scrap rubber to fine mesh rubber crumb is certainly new to the rubber recycling industry.

Cryogenic grinding is not the only size reduction process patented recently. Gould Incorporated have patented a secondary mechanical grinding process which involves grinding the coarse mesh scrap rubber while incorporating certain amounts of plasticisers with a tight nip mill (see Appendix B). A recent Australian size reduction process (2) uses a particular solvent mixture to swell the vulcanized scrap rubber before removing the swollen rubber matrix from its reinforcing components. The rubber is then ground to fine mesh rubber particles while in the swollen state. The solvent mixture is removed by evaporation and recovered (see Section 4.1B for more detail on this process).

With the advent of a frequent, large rises in the cost of petroleum oil and the fact that it is a limited and unrenovable raw material source, rubber recycling should become a more advantageous and beneficial proposition. It is likely that more recycling processes will be developed.

3.2 Statement and Analysis of Current Situation Regarding Scrap Rubber Arising

There are basically two forms of scrap rubber presently available, namely the uncured scrap and the cured scrap. The main difference is that uncured scrap rubber consists mainly of uncured or partially cured (the term 'scorched' is often used by the rubber technologist) rubber mixes or articles whereas the cured scrap comprises discarded or used rubber products (eg. scrap tyres), factory scrap and rejected rubber articles from the rubber processing factories.

(a) The Uncured Scrap can be divided into three groups. The first group can be considered as the top grade which consists mainly of out-of-specification rubber compound mixes, scorched or partially vulcanized stocks, contaminated and redundant mixes. This grade does not usually contain any reinforcing components such as fabric and steel, and are used to manufacture rubber products requiring lower physical properties.

The second grade arises mainly from out-of-specification rubber products prior to the vulcanization process. Hence it usually contains reinforcing components. This grade of uncured scrap rubber has been used to manufacture a variety of rubber products which require low physical properties for example rubber traffic cones, dustbin lids and mud flaps.

Soiled, contaminated or off-graded virgin synthetic rubber stocks from the rubber producers constitute the third group. Again these are used to manufacture rubber products in less crucial applications.

With the advancement in analytical chemistry where a compound can be identified easily and rapidly, coupled with better quality control and stock management forced by the more expensive raw rubbers and compounding ingredients, uncured scrap rubber has become a rare item. The major source of scrap rubber is therefore the cured scrap rubber.

(b) Cured Scrap can be classified into two categories, namely the factory scrap and the discarded or used rubber products. Rejected articles, moulding flashes, transfer moulding pads and injection moulding runners are common sources of cured scrap arising from a factory floor. Leaving rejects and spoilage aside, a 10% to 15% by weight of wastage through moulding flashes, transfer pads etc. is considered acceptable in the rubber processing industry. This percentage for an injection moulded product is an astonishing figure of about 30%. Recycling of this scrap would be financially attractive especially when an expensive specialty rubber is used. This has been done to a small extent but the common fear which is responsible for these specialised materials not being recycled into products lies in the very high technical specifications that are often associated with these specialised rubber containing products such as seals for the aircraft industry, and in the belief that the recycled scrap would cause the product to fail during service. The high cost of the recycling machinery (see Chapter 5 for some typical figures) further discourages the potential user from setting up an in-house recycling facility.

The other type of cured scrap comes from the discarded or used rubber products. Rubber shoes, conveyor beltings, hoses, tubings, tyres and tubes are some of the hundreds of articles made from rubber or contain a large proportion of rubber. The volume of rubber in the products is

not usually reduced significantly during their service life, hence these discarded rubber articles form a huge source of more rubber. These can be broadly categorised into tyre and tyre products, and non-tyre products.

(i) Tyre and tyre products: The tyre industry consumed about 45% by weight of all the rubber supply in the UK. Although a wide diversity of rubber-based products from rubber glue to giant earthmover tyres is manufactured by the tyre industry, the main product and the product which consumed the most rubber is tyres and its related products such as tubes and tyre repair kits. It was estimated (from the tyre sales figures of the original equipment and replacement markets) that some 20 million worn car/van tyres were turned into scrap each year in the UK (58). An estimate of 200 million worn tyres is discarded each year in the USA (62). Elsewhere in the developed world, the situation is similar. The worn tyres can be collected through the presently well established chain of tyre dealers and distributors who provide the major source of raw material for the rubber recycling industry.

The importance of worn tyres as a source of rubber and the environmental and pollution problems arising from them were subjects of several studies (for example Reference 53, 55, 59, 60, 65 and 127). In the UK, a Parliamentary Commission was appointed to study the reclamation and re-use of these worn tyres (58). In The USA, two research investigations (62, 69) were carried out to study the problems arising from their high 'stockpile' of discarded worn tyres.

Scrap worn tyres are looked upon as the main source of scrap rubber by most of the present scrap rubber recycling processes. Taking cryogenic grinding for example, special patented apparatus has been designed to handle a whole worn tyre (see for example References 76, 107, 111 and 106). Other processes, such as pyrolysis, also have similar capability. Where the recycling process is unable to handle whole tyres, there are many tyre comminutors or shredders available to reduce the physical size of the whole tyres. Many of these shredders, cutters or comminutors are the subjects of patent claims (see for example References 93, 98 and 101). There are also hammer mills and special (grinders which are able to grind the whole tyres into coarse particles (see for example References 86 and 95).

Another cured scrap rubber source related to worn tyres is the tread buffings and peelings (see Section 4.2B for discussion and quantitative estimate), which provide a very convenient form of starting material for most rubber recycling processes.

(ii) Non-Tyre Products: The remainder of the rubber finds its way into an even wider variety of rubber products. Conveyors, beltings, hoses, tubings, household appliances such as washing-up gloves, garden hoses, automobile parts such as oil seals, stationery such as rubber bands, mechanical products such as damp-proof course, anti-vibration mountings and bridge-bearings, and a great many more products which exploit the unique material properties of rubber. However, such a wide diversity of products is not of much help as far as recycling scrap rubber is concerned. Firstly, the problem of collecting and separating the discarded rubber articles from the rest of the refuse is not an easy task. Secondly, the large number of different types of rubber used make the sorting out and classification of the discarded rubber products into their appropriate types an almost impossible task. Lastly, but certainly not least, the economics of separating these rubber products from the high quantity of other refuse is not at all attractive. All in all, it seems that these miscellaneous rubber products are not a likely source of recycleable rubber hydrocarbon.

4.1 Process Availability

Conceptually, the technology for the recycling of scrap rubber, in particular scrap vehicle tyres, can be considered to be matured, as evident from the volume of scientific and technological literature published. The wide diversity of methods and the different routes each scientist/technologist has chosen, indicate that recycling of such a chemically complex material as scrap vulcanised rubber may follow several routes, thus yielding a wide range of products. As discussed previously, emphasis will be given to processes classified as Conventional Reclamation Processes and Size Reduction Processes. Other processes which have received considerable attentions will also be included.

An attempt has been made to distinguish between a technological concept and a physically available process. A technological concept is defined, for the sole purpose of this study, as a theoretically feasible process which can be draughted on paper and drawing board, and perhaps proven by small scale pilot plant operation, but yet to be exploited commercially. Patents are a rich source of information for such processes (A list of recycled rubber related patents are included in the references and bibliography section). These technologically feasible processes are described as Commercially Unavailable Processes.

Contrary to the Commercially Unavailable Processes, the Commercially Available Processes can be purchased without resort to research and development. Many of these processes have evolved from the former class of processes, and are often protected by patent claims. The major difference between the two classes is that Commercially Available Processes are or potentially economically viable. The presently operating processes are therefore classified under the Commercially Available Processes.

The versatility, maintainability and wear-deterioration characteristics of each process will be discussed in as far as obtainable data and information allow. Ability to handle a wide variety of types and forms of input, the output types and forms that can be produced, and the optimum operating capacity range are referred to as versatility. Maintainability is defined as the requirement and ease with which maintenance can be carried out. Durability against wear-and tear and

deterioration, and life expectancy of the machinery are the subjects of wear-deterioration.

Although it is possible to classify the processes in a general way, it must be noted that recycling facilities based on the same process principles are not necessarily identical. Each plant has unique features.

4.1A Commercially Available Processes

The processes are again classified under three categories; namely Conventional Reclamation. Size Reduction and Other Processes. The processes falling within each category employ similar technology. Details of the technology of the processes reviewed below are given in Appendix B.

a) Conventional Reclamation Processes

This category of process has evolved from the processes described in Section 3.1 (b) which have been in operation since the early days of the rubber recycling industry in the 1940s and 1950s. Modifications and improvements have been made to the original processes with the advancement in science and technology, and with the changing economic circumstances. The 'oil price crisis' of the early seventies and the overcapacity of the virgin rubber manufacturers, resulting in very competitive virgin rubber prices, falling demand for reclaimed rubber and several other factors have forced a large number of recycled rubber manufacturers out of business. The primary victims are the high energy input processes. This has been confirmed by our survey of recycled rubber manufacturers in Europe and North America (see Appendix A). In the United Kingdom, there is only one reclaimed rubber producer, who has been operating for some time.

These processes are classified under Commercially Available Processes simply because they are in commercial operation.

(i) The Digester Process

This process is currently still in used in both the USA and the UK. The operator of this process in the UK is Uniroyal Chemicals. A modified form of Digester is used. Modifications were made primarily to improve productivity, lower the energy requirement and improve product quality. The input to the Digester is essentially the same as a Reclaimator i.e. metal-free fine rubber crumb. Cracking, separating and grinding are vital production steps. The need for constant maintenance, the

unfavourable wear and deterioration characteristics, and the relatively high energy consumption of these production steps can be vital to the viability of this process.

The output from the Digester process is reclaimed rubber. Due to the batch production nature of the process, only one production capacity is optimum, which is the optimum capacity of the Digester. The inability to process in a continuous manner may constitute another weak point of the Digester process.

(ii) The Reclaimator Process

A Reclaimator provides the solution to some of the short comings of the earlier processes such as the Digester, or the Heater or Pan processes. The pressure required is supplied by the screw of the Reclaimator while the reclaiming heat is generated by mechanical working and friction between the scrap rubber crumb, the rotating screw and the stationary barrel. The major advantages are that Reclaimator operates continuously, and it is essentially a dry process. It thus eliminates the need for high energy consuming driers.

The input vulcanized scrap rubber has to be finely ground, about 30 mesh, metal and fabric free. The cracking separating and grinding are therefore inevitable, incurring additional operating and energy costs. The Reclaimator itself, like the Digester, is a large consumer of energy. Refining the output into a consistent product not only requiring an additional production stage, but also consuming a large amount of energy.

The output from the Reclaimator is more versatile than the Digester process, it can be in the form of bales, slabs or pellets. A change in output rate can theoretically be achieved with comparable ease by altering the screw speed of the Reclaimator, the reclaiming temperature and the type of chemical reclaiming agents used. Optimum levels of production can hence be obtained, giving Reclaimator a further degree of versatility.

b) Size Reduction Processes

Size reduction is referred to here as the formation of fine rubber powder or crumb. Conventionally, rubber crumb can be obtained by mechanically grinding pieces of vulcanized scrap rubber with grinding mills. The

reclaimed rubber producers use these fine rubber crumb as their input. In order to distinguish between crumb production as an input preparatory step and as a saleable output production process, emphasis is given here only to size reduction processes producing saleable output. However, it should be pointed out that at the present time the majority of rubber crumb is derived from mechanical grinding. The main drawbacks of conventional mechanical grinding is its inability to achieve particle size smaller than about 40 mesh in sufficiently large quantities, and without creating undue heat degradation of the rubber particles. A typical mechanical grinding process is described in the cracking, separating and grinding steps of the Conventional Reclamation Processes in Appendix B.

The following size reduction processes are reported to be commercially available.

(i) Cryogenic Grinding - The Air Products Process

This Air Products process is based on United States of America Patent 4 025 990. It is essentially a system of cracking, separating and grinding whole tyres into fine rubber crumb, steel and fabric material.

Like all cryogenic grinding processes, it is based on the principle of cryogenic embrittlement of rubbers. Efficient usage of cryogenic media, generally liquid nitrogen, is therefore of primary importance. The Air Products process employs cryogenic grinding in two stages, first to liberate the reinforcing components from shredded tyre pieces, then grinding the metal and fabric free rubber to desirable sizes. It is also important to have an efficient fabric and metal separation system so as to avoid "bottlenecks" in the process and increase productivity.

The input to the process is whole tyres, both steel and fabric reinforced types. Output takes the form of fine rubber particles, the size of which can be easily altered by the size of the final screen. Information regarding maintain-ability, wear and deterioration characteristics are not available, however, considerable wear in the tyre shredder and grinders will be anticipated.

George H. Hughes of Birmingham, and Winson BV of Holland are reported to use this process or a version of it.

(ii) Cryogenic Grinding - The Bellaire Hydraulics Process

The process is based on Vernon Richardson's US Patent 3 718 284. Two units of scrap tyre recycling facility based on this process have been reported to be in operation in USA.

The input whole tyres of steel or fabric types are frozen in two stages; then precooling by liquid nitrogen sprays followed by a liquid nitrogen bath. A roller crusher and a grinder are used to pulverise the embrittled tyre while a belt magnet removes the ferrous components continuously.

The output crumb is less than 6.35 mm in size, containing most, if not all, of the fabric present in the input tyres. High metal contamination may be anticipated.

(iii) Cryogenic Grinding - The Hazemag Process

This process is developed by Hazemag Dr E Andreas KG of Germany, and is based on a patented hammer mill (US Patent 3 997 121) and a 'Novorotor' mill of the company's design.

Both steel and fabric tyres can be processed. Whole tyre input is cooled to embrittlement by liquid nitrogen sprays, pulverised in the hammer mill, separated in a classifying sieve, ground in the Novorotor mill with the excess liquid/gaseous nitrogen from the freezing tunnel, and the output rubber crumb of less than 1 mm size is collected in a cyclone.

(iv) Cryogenic Grinding - The BOC-KEK Process

This process is jointly developed by BOC and KEK. The freezer/conveyor is designed by BOC, while KEK is responsible for the grinding and sifting devices.

The input to this process is metal and fabric free, 6 mm rubber granules. The granules are frozen in the freezer/conveyor while being conveyed to the suction feed apparatus. The embrittled granules are mixed with a predetermined proportion of air, and then feed to the pinned disk mill which subsequently grinds the granules into fine particles. The fine particles are sieved with a centrifugal sifter into two fractions; the main output of fines with size about 400 μm , and the oversize. Wearing of pins in the mill may be expected.

(v) Cryog grind & Chemical - The Trellfax Process

This process is developed by Trelleborg AB of Sweden. A plant on this

process is reported to be in operation is Surahammaer, Sweden License for this process may be obtained from Trelleborg AB.

The process is divided into two stages. The first stage is in effect, cryogenic grinding, while the second involves chemical reclamation of the cryogenically ground rubber crumb. Two types of output are produced, fine rubber crumb from the first stage and Trelleborg Cold Reclaim (TCR) from the second.

In the first stage, shredded whole tyre input of both steel and fabric constructions is cryogenically pulverised in a hammer mill, followed by a series of separators which remove non-rubber components. Fine and coarse fractions are obtained by screening. The fine fraction is fed straight into the screens, while the coarse fraction is ground in a toothed disk mill before passing through the screening step. These grinding, separating and screening operations are repeated with grinding carried out cryogenically. The output of this stage can be sold as fine rubber crumb (about 40 mesh).

In the second stage of the Trelleborg process, the fine crumb is blended with peptisers and plasticisers in a powder mixer. The chemical reagents devulcanize the surface of the rubber particles. This is claimed to enhance physical properties of the rubber compounds incorporating this reclaim. The output from the process is the Trelleborg Cold Reclaim (TCR) which is in powder form. The TCR reclaim may also be rolled into sheets or slabs.

(vi) Swell & Grind - The Gould Process

This Gould process follows a distinctly different route from the other size reduction processes. The patented (US Patent 4 046 834 and 4 049 588) process uses the swell weakening property of vulcanized rubber. Gould Inc. of Ohio, USA is reported to have installed a 1500 tonnes per year plant operating this technique.

The input rubber crumb of 40 mesh, metal and fabric free, is allowed to imbibe as much of a water miscible solvent as possible. This is followed by grinding the solvent weakened vulcanised rubber network into very fine particles. Water is added during or after the grinding to remove the solvent. Finely ground rubber particles are obtained by separating the liquid phase and drying the solid phase. Solvent may be recovered

from the liquid phase. The process is claimed to yield rubber crumb output with 90% particles of less than 20 μm .

c) Other

(i) Microwave - The Goodyear Process

This patented (UK Patent Application 2 028 835 A) process utilises the microwave technology. Goodyear has used this process to recycle factory scrap rubber from its hose and belting plant in Lincoln (Nebraska, USA).

The metal and fabric free scrap rubber input is granulated to sizes of about 9.5 mm, and then exposed it to a controlled dosage of microwave energy which causes chemical bonds in the vulcanized rubber network to breakdown. Devulcanization is carried out continuously. The devulcanized scrap rubber is refined and plied into slabs.

The main limitation of the process is that it can only devulcanize scrap rubbers which are polar or contain a polar additive.

4.1B Commercially Unavailable Processes

The majority of these processes may be classified as size reduction and pyrolysis-solution processes.

a) Size Reduction Processes

(i) Swell & Grind - The Dobozy Process (2)

This process involves removing of bead wires from the tyre and shredding it into large pieces. After submerging these pieces in a chemical bath for several hours, causing them to swell and soften, they are reduced to crumb. Fabric and metal reinforcements can be easily separated by simply shaking the chemical softened tyre pieces. The chemical is recovered and the crumb returns to its rubbery state. The process has been patented in Australia.

(ii) Activated Crumb - The Dunlop Process (80)

This patented process (UK Patent 1554 858) (80) involves heating the surface of scrap vulcanized article, such as tyres, at a high temperature of about 2500°C for a short time, of about 0.1 second, rasping off the heat treated surface and granulating it into fine particles. The patent covers both the method and the apparatus for carrying out this process. Development work is still in progress. Figure 4.1 shows the surface of an activated crumb particle.

b) Pyrolysis - Solution Processes

These processes are based on the chemical destruction of the vulcanized rubber network. The degree of destruction dictates the product or products yielded. Incineration processes without material recovery are not included.

(i) Tyrolysis - The Warren Spring Laboratory Process (32, 33, 34)

This is a pyrolysis process designed and developed by the Warren Spring Laboratory of the Department of Industry, specifically for processing scrap rubber tyres. Shredded tyres are fed into the top of a vertical reactor, as they drop to the bottom, they are heated directly with hot combustion gasses at a controlled temperature. The hydrocarbon components of the tyre decompose into oil and gas, while carbon black and other non-organic additives are converted into char. The char and residue, mainly steel reinforcement, are removed from the bottom of the reactor through a lock hopper system. A yield of about 50% oil, 40% char black and 10% gas is reported.

(ii) Destructive Distillation - The US Bureau of Mines Process

Developed jointly by US Bureau of Mines and Firestone Tire and Rubber Company (35, 42, 53, 60, 62), the destructive distillation process for pyrolysing scrap tyres can be operated in batch or continuous manner. In a batch-type process, feedstock of whole or shredded tyres are fed into a retort and heated to a desirable temperature. The organic components decompose into gas and oil. The oil is collected in a series of air-cool traps, water-cooled condensers and electrostatic precipitators. The gases are passed through a series of scrubbers which remove ammonia, carbon dioxide and hydrogen sulphide.

On a batch operation, the process yields an average of 40-50% char black, 20 - 50% oil and 5 - 20% gas, while a continuous operation yields 30 - 50% and 10 - 20% of the respective products.

(iii) Tosco II - The Goodyear Process (36, 40, 90)

This process is based on the oil shale cracking process developed by Tosco Corporation (USA). Preheated shredded scrap tyres are fed into an inclined pyrolytic drum with heated ceramic balls. The shredded tyre pieces are mixed thoroughly with the hot ceramic balls and conductive heat transfer between the balls and the shredded tyre causes retorting to occur within a short residence time. The pyrolytic products flow

into a cyclone separator where suspended solids and ceramic balls are separated from the gases. The char solid is again separated from the ceramic balls, and is cooled. It then passes through a magnetic separator and a screen to remove metal and fibre-glass components. The ceramic balls are returned to the ball heater to be heated and reused.

The gases and vapours flow from the top of the cyclone into a fractionation system where they cool to produce various liquid oil fraction, and uncondensed gas. The gas may be used to reheat the ceramic balls. Additional heat energy is recovered from the hot flue gases from the ball heater by using it to preheat the shredded tyre pieces.

A 15-ton per day pilot plant is reported to be in operation (36).

(iv) Fluidised Sand Bed - The Kaminsky - Sinn Process (37, 41)

The excellent heat transfer property of a fluidised bed is explored in this pyrolysis technique. The fluidised medium is silica sand in this German process, while carbon black has been used in Japan. Whole tyres are fed, through a gas-tight charging system, into the vertical fluidised bed reactor. The preheated pyrolysis gas, also acts as fluidising gas, enters the reactor from the bottom and leaves through a cyclone carrying with it the pyrolytic products of gas, oil and char black, steel cords and other reinforcing components of the pyrolysed tyres are removed by a special tiltable grate. Char black is precipitated in the cyclone. The oil is condensed in a series of cooling system and an electrostatic precipitator. The gas fraction is used to heat the pyrolytic gas. A pilot plant has been reported to be in operation (37).

(v) Depolymerised Scrap Rubber (DSR) Process (59, 104)

The DSR process is developed by Firestone Tire and Rubber Company (USA) (104). Shredded scrap rubber tyres are heated with an aromatic rubber processing oil in an autoclave reactor at about 275°C for between 12 to 24 hours. Dissolution of the rubber hydrocarbon takes place. The processing oil acts as a solvent as well as the heat transfer agent. As the depolymerisation reaction proceeds, the product DSR also acts as a solvent and heat transfer agent, thus more scrap rubber can be added. By continuous addition, the composition of the DSR asymptotically approaches 100% rubber hydrocarbon. The textile reinforcement of the tyre is melted, dissolved or dispersed in the DSR, The undissolved reinforcement components of the tyres, such as glass-fabric and steel,

are removed by screening the light oil diluted DSR. Carbon black and other inorganic fillers are left as a dispersion in the DSR. The carbon black can be isolated by solvent extraction.

4.2 Forms of Input and Output

4.2A General Considerations

As described in Section 3.2, the most abundant source of scrap rubber is , and will continue to be in the form of scrap vehicle tyres, in particular steel belted tyres. Consequently, processes which at present are not capable of handling steel-belted tyre input may find it increasingly difficult to secure a steady supply of raw material input.

A process, from the standpoint of input and output forms, can be considered as a primary, a secondary or a complete process. A primary process is one which accepts the most crude input i.e. scrap whole tyres, and produces an output which cannot be used for rubber compounding. A secondary process accepts the output from a primary process and converts it into a product acceptable for incorporation into rubber compounds. A complete process includes both. In this respect, the Digester, Reclaimator, Air Products, Hazemag and the Trellfax processes are complete processes. The Bellaire Hydraulics process which generates > 6 mm crumb output is considered a primary process, whilst BOC-KEK, Gould and the microwave processes are secondary. Tyre retreading which produces tread buffings, in this context, may be regarded as a primary process. In as far as recycling of scrap rubber into rubber products is concerned, a process is desirable to be a complete one, thus dispensing the need to rely on the supply of a particular form of input. Taking the example of tread buffings, which can be used as an input for several processes, it is known that the supply of tread buffings is particularly susceptible to demand fluctuation, a sudden surge in demand will create a shortage in its supply. Upgrading of a process can be achieved. A primary process such as the Bellaire Hydraulics process, can be upgraded to a complete one by combining it with a secondary process such as the BOC-KEK process. Similarly, upgrading of a secondary process can be achieved by combination with a primary.

Table 4.1 summarises the forms of input and output for the Commercially Available processes. The forms of inputs are described in more detail in Section 4.2 B and the outputs in Section 4.2C. Little data is

Table 4.1 : Summary of Input and Output for the Commercially Available Processes

PROCESS	INPUT		OUTPUT	
	FORM	COMMENT	FORM	COMMENT
<u>CONVENTIONAL RECLAMATION PROCESSES</u>				
Digester	Whole Tyres: steel* & fabric constructions	Require to reduce to 6-10 mm particles and metal-free.	Reclaimed Rubber in Slabs & Bales	Can be easily accepted by conventional processing equipment.
Reclaimator	Whole Tyres: fabric construction	Require to reduce to 30-40 mesh crumb, metal & fabric-free.	Reclaimed Rubber in Pellets, Slabs & Bales	Can be easily accepted by conventional processing equipment as well as powder mixing equipment.
<u>SIZE REDUCTION PROCESSES</u>				
Cryogrinding-Air Products	Whole Tyres: steel & fabric constructions	Shred, embrittle and pulverise.	Crumb of desirable size	Crumb size depends on final screen size.
Cryogrinding-Bellaire Hydraulics	Whole Tyres: steel & fabric constructions	Embrittle as whole tyres, pulverise, separate and grind.	Crumb of > 6.35 mm	Containing high proportions of fabric and metal contaminations.
Cryogrinding-Hazemag	Whole Tyres: steel & fabric constructions	Embrittle as whole tyres, pulverise, separate and grind	Crumb of < 1 mm	
Cryogrinding-BOC-KEK	Crumb, metal & fabric free, 6 mm	Cracking, separation and initial grinding stages not included in the process.	Crumb of ~ 400 µm.	

*It is doubtful if a high proportion of steel-belted tyres can be accepted by the conventional mechanical separation stages of the Digester process. A figure of 5 to 10% is said to be optimum (123).

PROCESS	INPUT		OUTPUT	
	FORM	COMMENT	FORM	COMMENT
Cryogrinding & Chemical - Trellfax	Whole Tyres: steel & fabric constructions	Crack, embrittle pulverise, separate and grind. TCR requires 30-40 mesh crumb, metal & fabric free.	(i) Crumb of ~ 40 mesh (ii) TCR Reclaim in powder or slabs.	2 output types can be obtained. TCR reclaim can be accepted by both conven- tional and powder processing equipment.
Swell & Grind - Gould	Crumb of 30-40 mesh, metal & fabric free	This makes it a secondary process. Imbibe solvent to swell, grind, solvent removal and dry.	Crumb of 90% < 20 µm	
<u>OTHER PROCESSES</u>				
Microwave- Goodyear	Granule of ~ 9 mm, metal and fabric free	Only polar or polar-additive containing scrap rubber can be processed.	Devulcani- sed rubber in slabs and sheets.	Can be accepted by conventional processing equipment.

available concerning the physicochemical properties of the products of these processes. Some of the relevant information contained in the literature is included in Section 4.2 C.

4.2B Inputs

(i) Whole Scrap tyre

This is the most abundant and easily obtainable source of scrap rubber. An estimate of about 20 million scrap tyres are discarded each year in UK.

The tyre rubber compound consists of at least 3 types of rubber, such as natural rubber, SBR (styrene-butadiene rubber) and butyl rubber. They are contained in more than 5 rubber compound recipes, such as the tread, side-wall, inner-lining, apex strip and chafer strip compounds. Each of the compound has its special characteristics. Segregation of each rubber compound is extremely difficult, if not impossible.

The rubber compounds are of high quality, the exact compositions of which vary with different tyre types, construction, the part of the tyre and the maker of the tyre.

It has at least two reinforcing components, i.e. the bead wire and the fabric carcass and belt, and three components in the case of steel-belted tyres, which have to be separated.

Textile members can be separated more easily by conventional mechanical means such as a system based on scalping screens, reel beaters and air flotation tables. Steel members can be liberated more easily by cryogenic pulverisation.

A typical worn passenger car tyre in the UK weighs about 5.8 kg of which about 70% (4.1 kg) is rubber compounds. A typical worn truck tyre weighs about 40.0 kg. The figure for worn truck tyre is less meaningful as there is a wide variation in the weight proportion of rubber compounds and other components. Hence all steel truck tyre of the same weight as a textile truck tyre will contain considerably less weight of scrap rubber.

Bulky toroidal shape of tyres requires expensive transportation and is difficult to handle. Pre-treatment of shredding, chopping and cracking

is often necessary in most recycling processes.

Figure 4.2 shows a sample of metal-free cracked tyre stock for the Reclaimator process. Figure 4.3 shows the separated fabric lint from the same process.

(ii) Tyre Buffings

Arises as a by-product from tyre retreading when a layer of rubber is removed from the crown (tread portion) of a tyre to reveal an unoxidised surface and to obtain a uniform circumference.

Buffings consist mostly of high quality tread rubber, and may be contaminated with small quantities of stone, glass and metal.

An average of 1 kg is removed from a worn passenger car tyre while that for a worn truck tyre is 10 kg (58). Estimated buffings supply from tyres retreaded amounts to 12,721 tonnes in 1979.

The size and shape of buffings depends on the type of rasp used. Buffings are generally in the form of thin narrow shreds of about 25 mm long. Peelings, i.e. long thin strips of rubber (a few metres long) are commonly obtained from rasping truck tyres.

It is possible to obtain finer mesh crumb such as 5 - 10 mesh from some tyre buffings.

Buffings would be a convenient form of input to the rubber recycling processes. The supply of buffings is expected to decline (see Table 2.4 on figures of tyres retreaded).

(iii) Crumb

It can be obtained in a wide range of sizes. These could have been resulted from a primary process such as the Bellaire Hydraulics process which produces crumb of >6 mm.

Fine crumb input suffers the disadvantages of:

- (i) high cost of preparation,
- (ii) heavily relying on the available supply of such crumb,
- (iii) uncertainty of the properties of the crumb.

4.2C Outputs

(i) Reclaimed Rubber

Usually in the form of sheets, slabs or bales. Packaging, transportation and storage of these forms of reclaimed rubber are similar to virgin rubbers, and can be accepted by conventional processing equipment. It can be easily incorporated into rubber compounds. Figure 4.4 shows the plied-nature of a slab of reclaimed rubber. Figure 4.5 through 4.26 show the micro-surfaces of the various grades of reclaimed rubber from worldwide sources.

Figure 4.5 shows a consistent and well-refined reclaimed rubber (source: United Reclaim Ltd, UK, Whole Tyre Reclaim R10). The wavy surface is due to the frictional nature of the refining operation. Figure 4.6 shows the surface of a sub-standard product from the same source, which contains a vulcanized particle that has not been properly devulcanized or refined.

Due probably to the refining mill operating at tight-nip and high friction ratio, a single ply of about 50 μm thickness has a smooth and a rough surface. The former is found on the high speed roll side while the latter is on the slow speed roll side.

Figure 4.7 and 4.8 show a smooth and a rough surface of Uniroyal Whole Reclaim 411. Figure 4.7 also shows the plied nature and a small piece of undigested fabric. More short strands of fabric can be in Figure 4.8 which also shows a vulcanized rubber particle. Note that the fabric contamination is less severe in the United Reclaim R10 sample (Figure 4.5).

Figures 4.9 and 4.10 show rough surfaces of two grades of a German reclaimed rubber at equal magnifications. Semi-devulcanized particles can be observed in both samples but particle sizes of about 100 - 150 μm is common with the first grade (Figure 4.7) while that for the second grade is about 200 - 300 μm .

Figure 4.11 and 4.12 show the rough surfaces of two grades of a French product of equal magnifications. The second grade D I W (Figure 4.12) shows vulcanized particles of 200 - 400 μm sizes while the particles of the first grade sample (Akron) appear only as ripples, indicating a well-devulcanized and refined product.

Figure 4.13 shows the rough surface of a Dutch sample, P58R. The micro surface structure is similar to that of the German second grade with comparable particle sizes.

Both the Indian samples are highly contaminated with fabric as shown in Figure 4.14 and 4.15. Lumps of vulcanized particles can be seen in the second grade sample (Figure 4.15).

Pelleted reclaimed rubber is packed in bags. Pellets tend to adhere together when not properly stored. Both conventional and powder processing equipment can be used with easy incorporation. Figure 4.16 shows pelleted reclaimed rubber sample from a Reclaimator process. Notice the fine particles, and the parting compound which prevent pellets from sticking together.

(ii) Rubber Crumb

Usually in the size range of 50 mesh (300 μm) to about 6 mm. It is claimed that the smaller the particle size, the better it is retaining physical properties (14). Rubber crumb is usually packed in 50 kg bags. Crumb tends to adhere together when under pressure over a period of time, therefore requires to be properly stored.

Figure 4.17 shows a sample of conventional ambient ground 40 mesh whole tyre crumb (source: United Reclaim Ltd, UK). Note that the particles have sharp corners.

In Gould R20 crumb, 90% of the particles are claimed to be less than 20 μm in effective diameter. A particle size distribution for this product is given in Figure 4.18, together with that for 40 mesh crumb and Trellfax TCR reclaim. Figure 4.19 shows a sample of the product. Stick-slip behaviour of rubber tearing is apparent in some particle surfaces. The scaly surface produced by stick-slip tearing is shown in Figure 4.20.

Figure 4.21 shows a sample of the Trellfax TCR reclaim. In the Trellfax process, rubber crumb is obtained from first cryogenically pulverising shredded tyre, followed by ambient or cool grinding using a toothed disk mill. Cryogenic grinding is evident from the sharp angular geometry of the particles. Surface roughness due to particle surfaces is evident from the close-up photomicrograph of a particle, Figure 4.22.

Figure 4.23 through 4.26 are photomicrographs of a sample of cryogenically ground rubber crumb. The sharp angular geometry is again evident (see Figure 4.23). Close-up photomicrograph of a particle surface, Figure 4.24, shows more evidence of a brittle fracture, as seen in thermoplastics (199). Figure 4.25 and 4.26 show that the fabric and metal reinforcements are cleanly removed by this process.

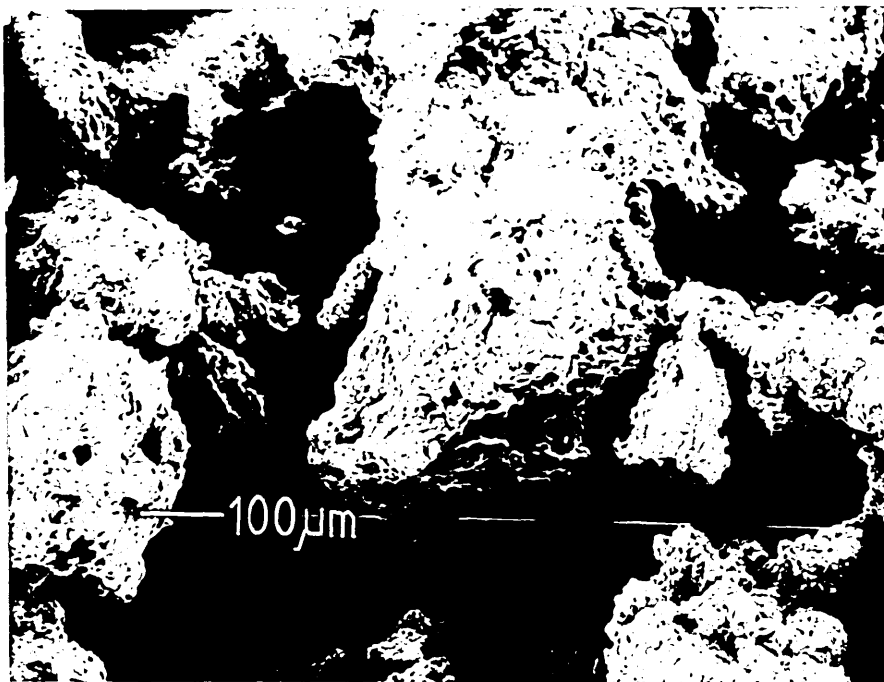


Figure 4.1 Activated Rubber Crumb

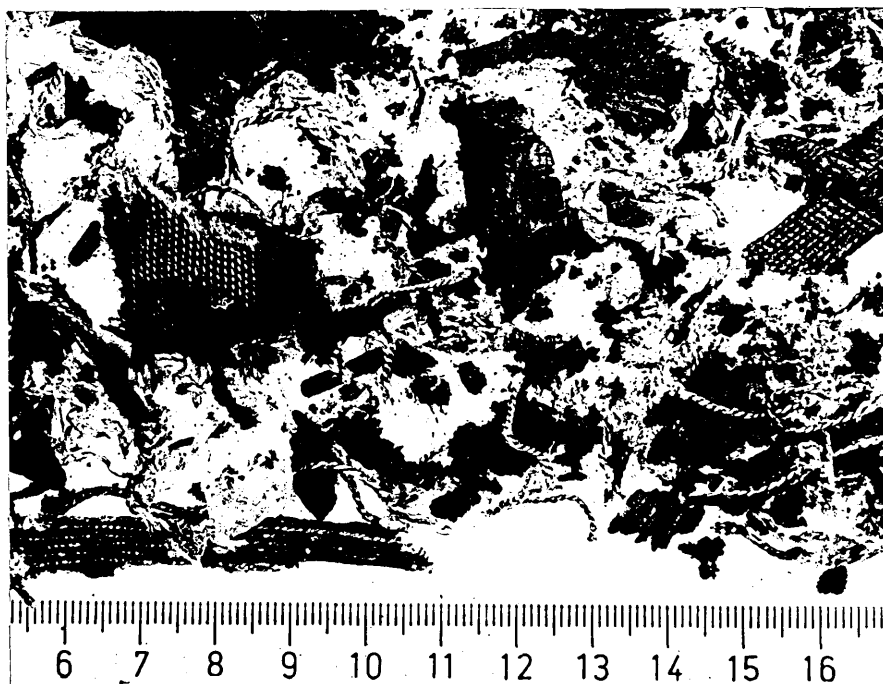


Figure 4.2 Metal-free cracked tyre stock
from the preliminary tyre cracking
stage of the Reclaimator process.



Figure 4.3 Separated fabric lint from the Reclaimator process.

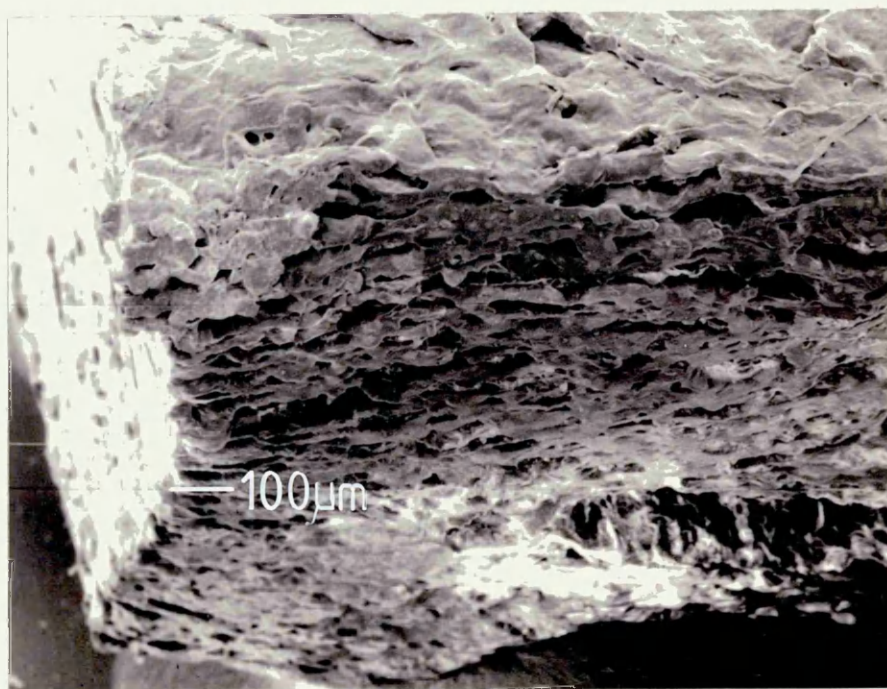


Figure 4.4 A slab of whole tyre reclaimed rubber showing plied nature.



Figure 4.5 Orange-peel nature of a well-refined reclaimed rubber from United Reclaim Ltd, UK (WTR R10)

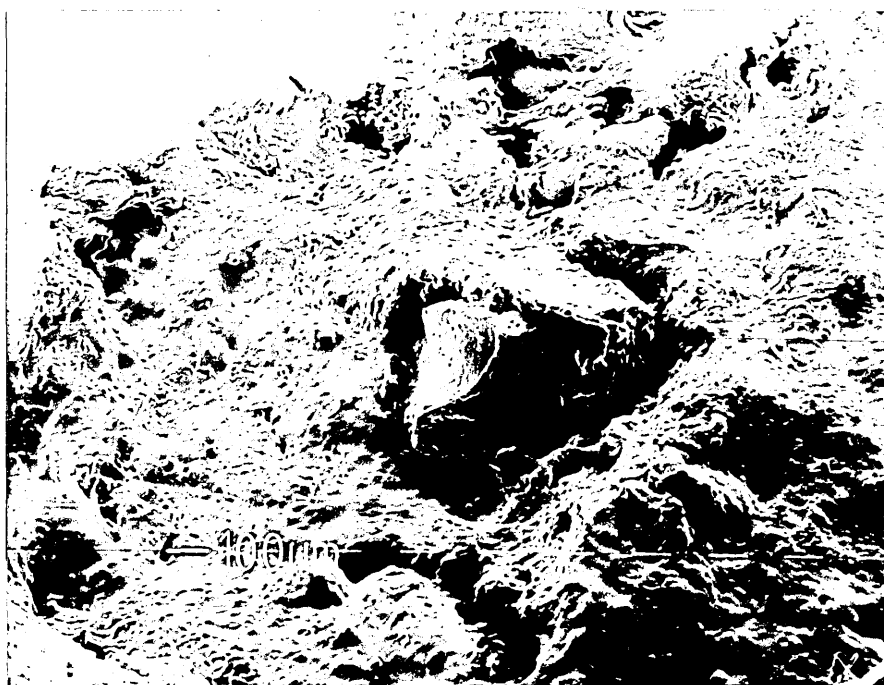


Figure 4.6 Sub-standard sample of WTR R10 showing a vulcanized particle.

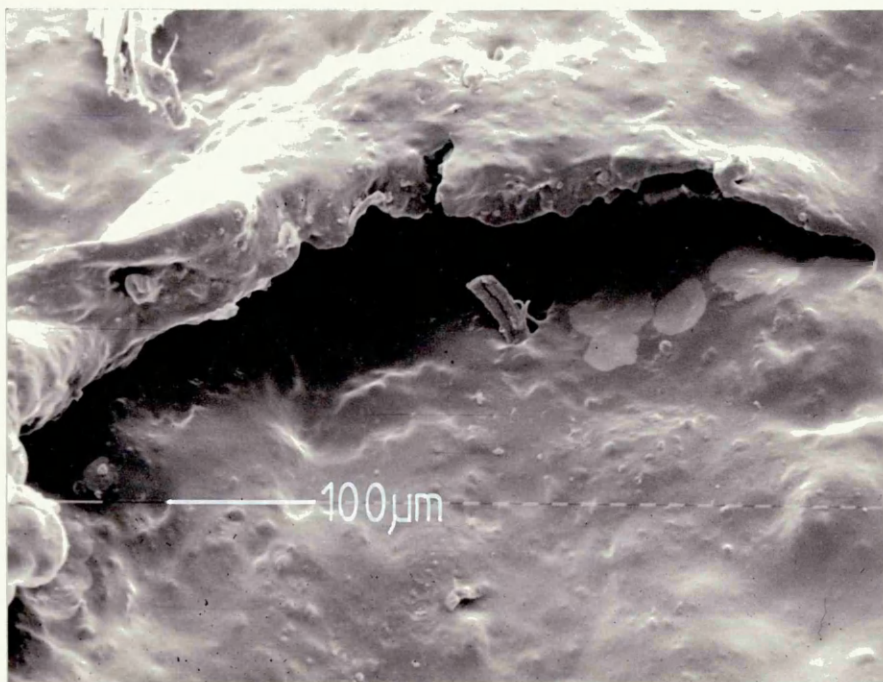


Figure 4.7 Uniroyal whole tyre reclaim 411 (UK) showing ply and fabric contamination.

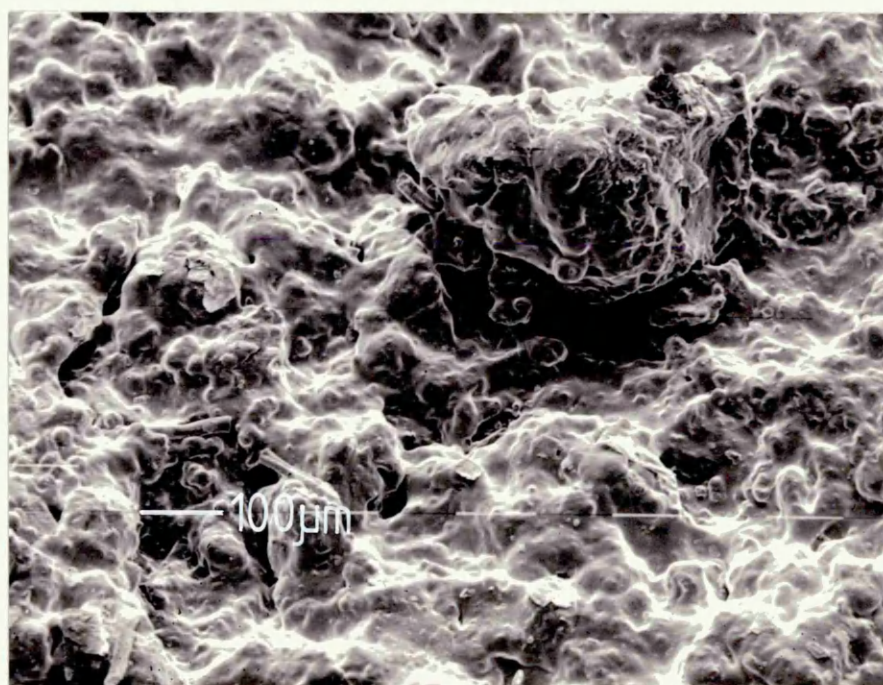


Figure 4.8 Uniroyal 411 sample showing a vulcanized particle and fabric contamination.

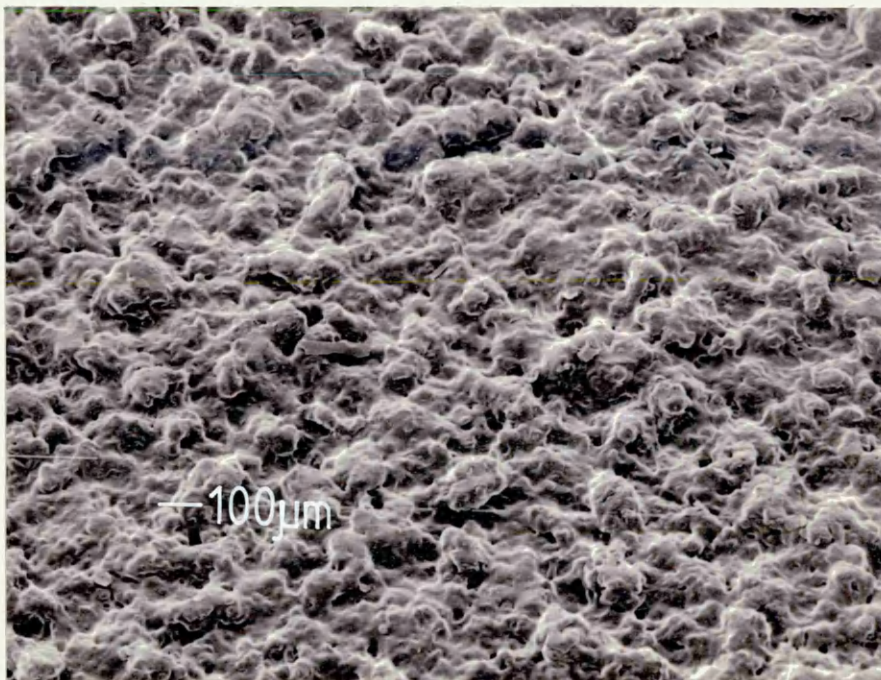


Figure 4.9 Hannau (W. Germany) sample, first grade whole tyre reclaim.

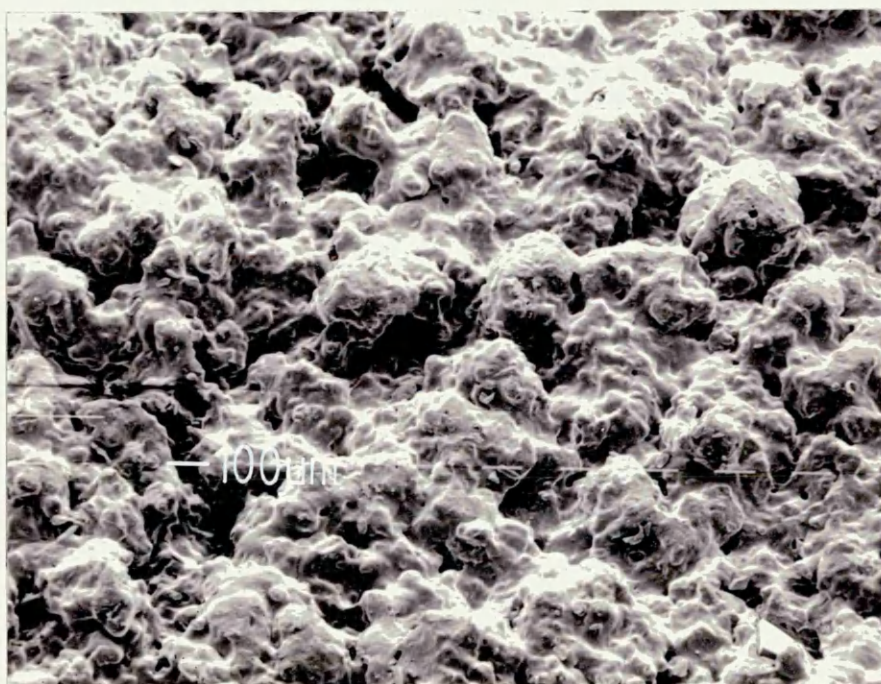


Figure 4.10 Hannau (W. Germany) sample, second grade whole tyre reclaim. Note the particle size difference between first and second grades.

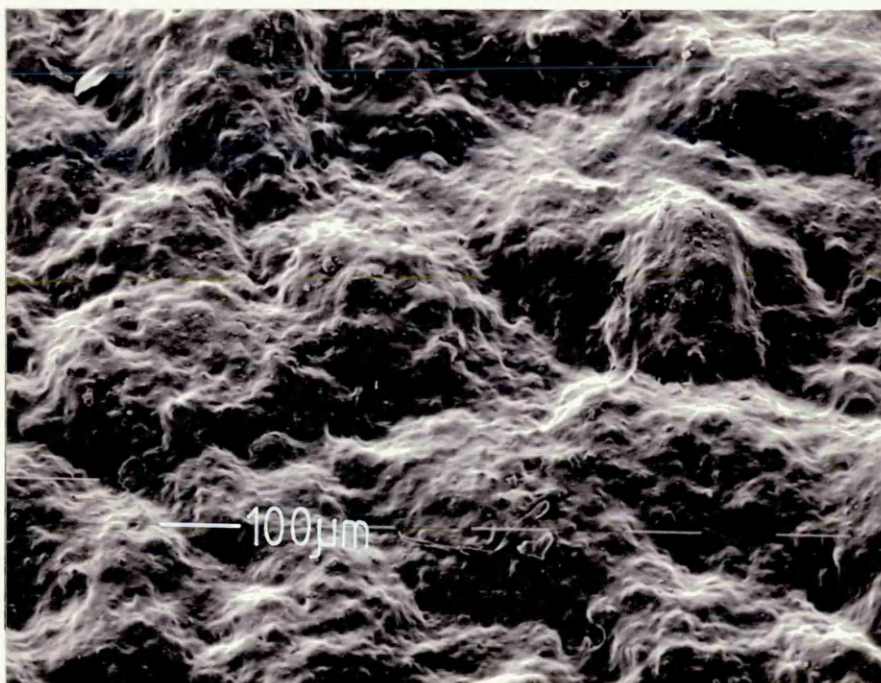


Figure 4.11 Wattlez & Cie (France) whole tyre reclaim sample, first grade, Akron.

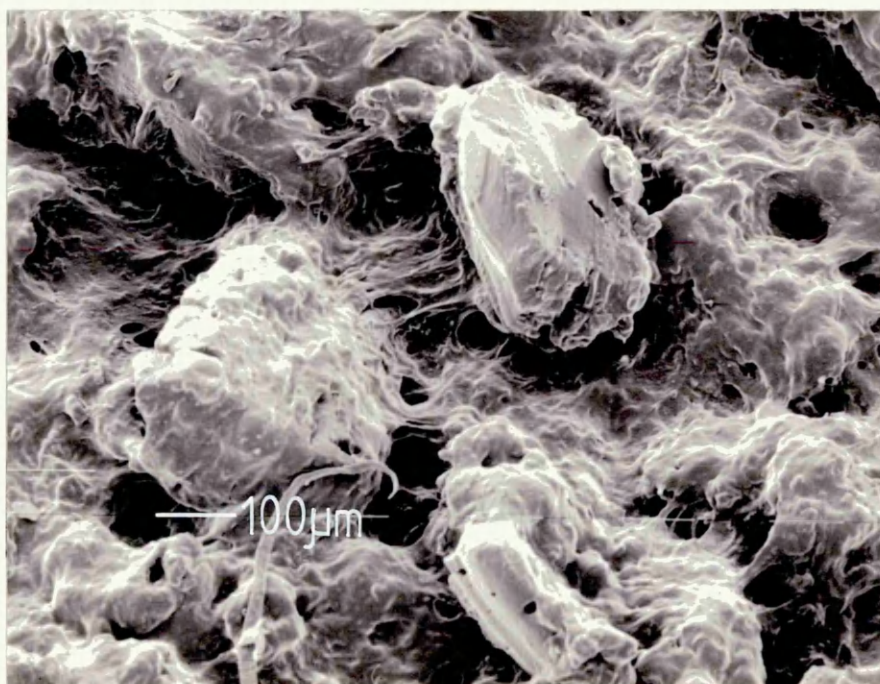


Figure 4.12 Wattlez & Cie (France) whole tyre reclaim sample, second grade, DIW shows large vulcanized particles.

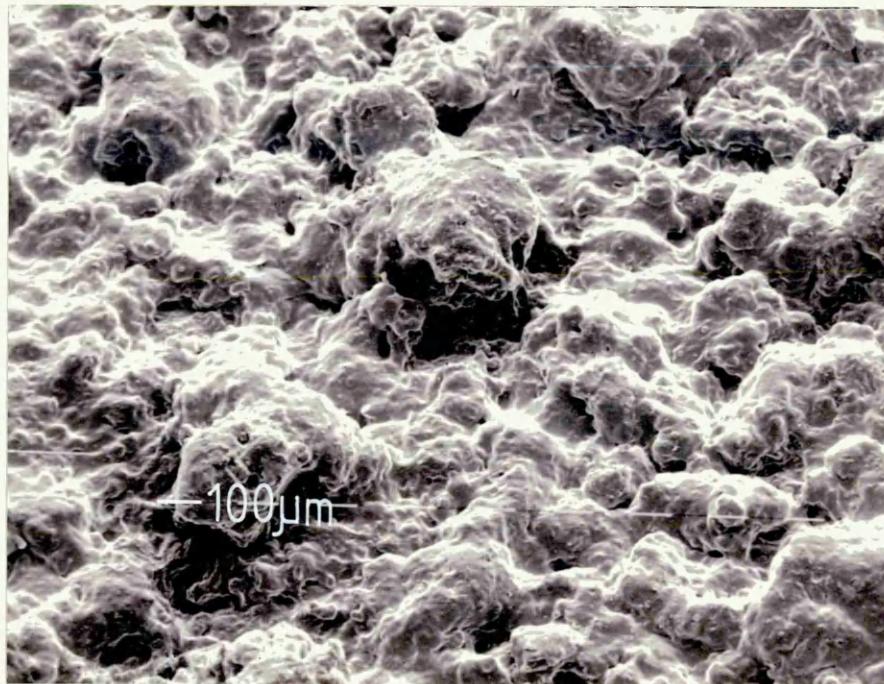


Figure 4.13 Vredestein Radium (Holland), whole tyre reclaim P58R

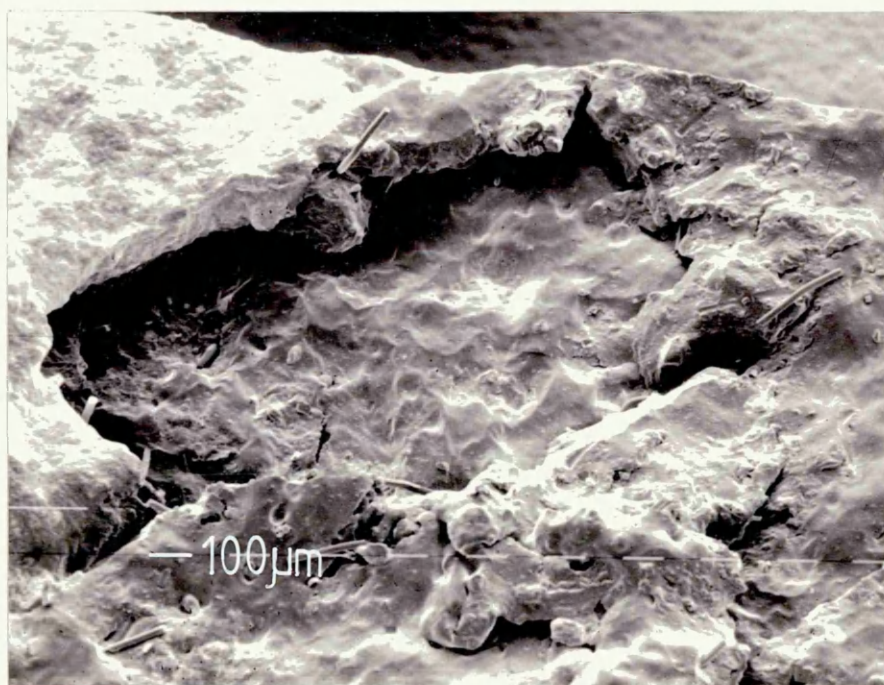


Figure 4.14 Rubber Reclaim Co. of India, first grade WTHR sample, showing ply and fabric contamination.



Figure 4.15 Rubber Reclaim Co. of India, second grade WT sample, showing high degree of fabric contamination.

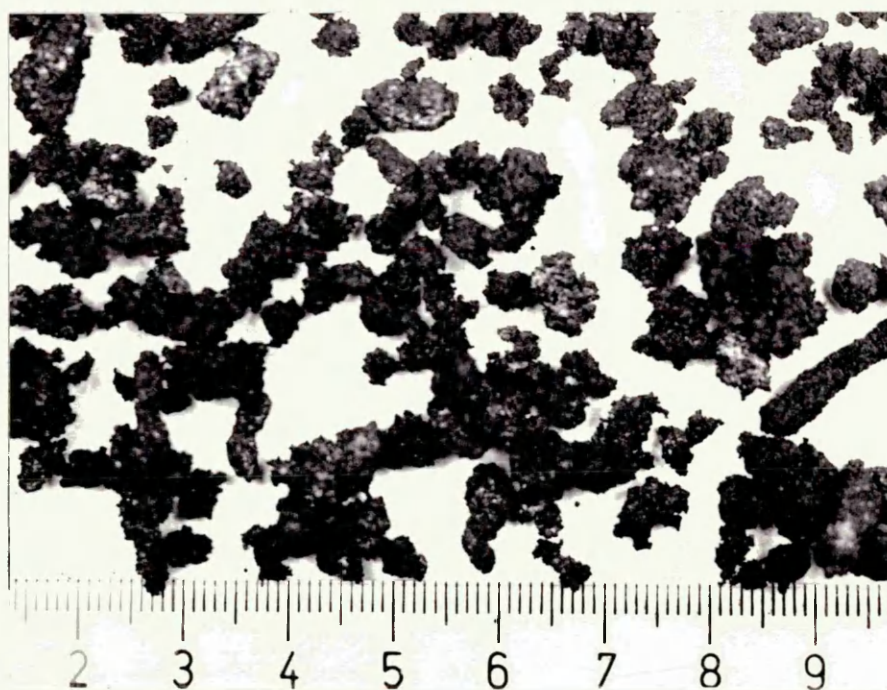


Figure 4.16 Pelleted whole tyre reclaim from a Reclaimator process (United Reclaim Ltd)

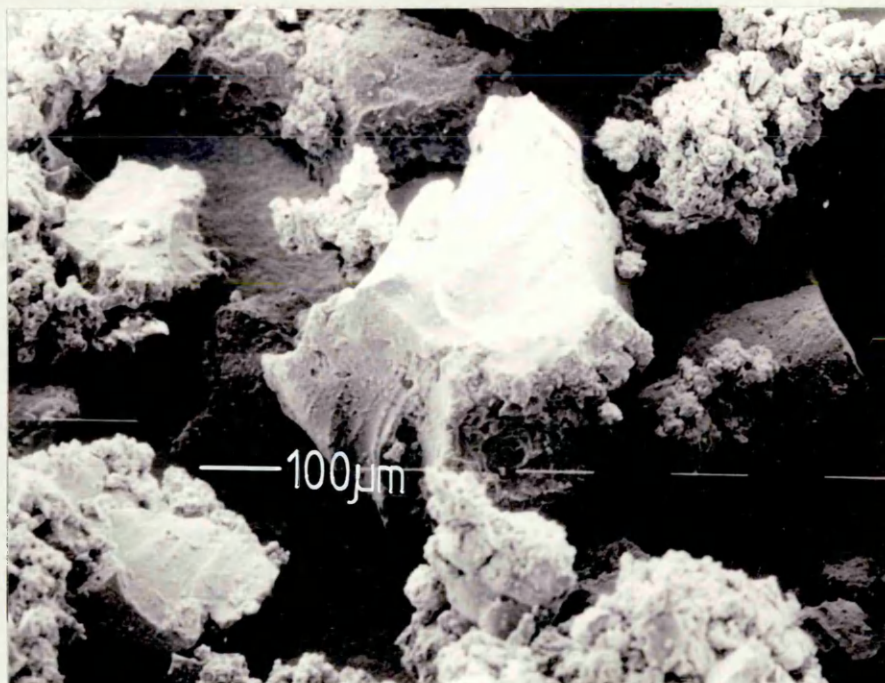


Figure 4.17 Conventional ambient mechanically ground
40 mesh crumb. (United Reclaim Ltd)
(The fine particles are parting agent.)

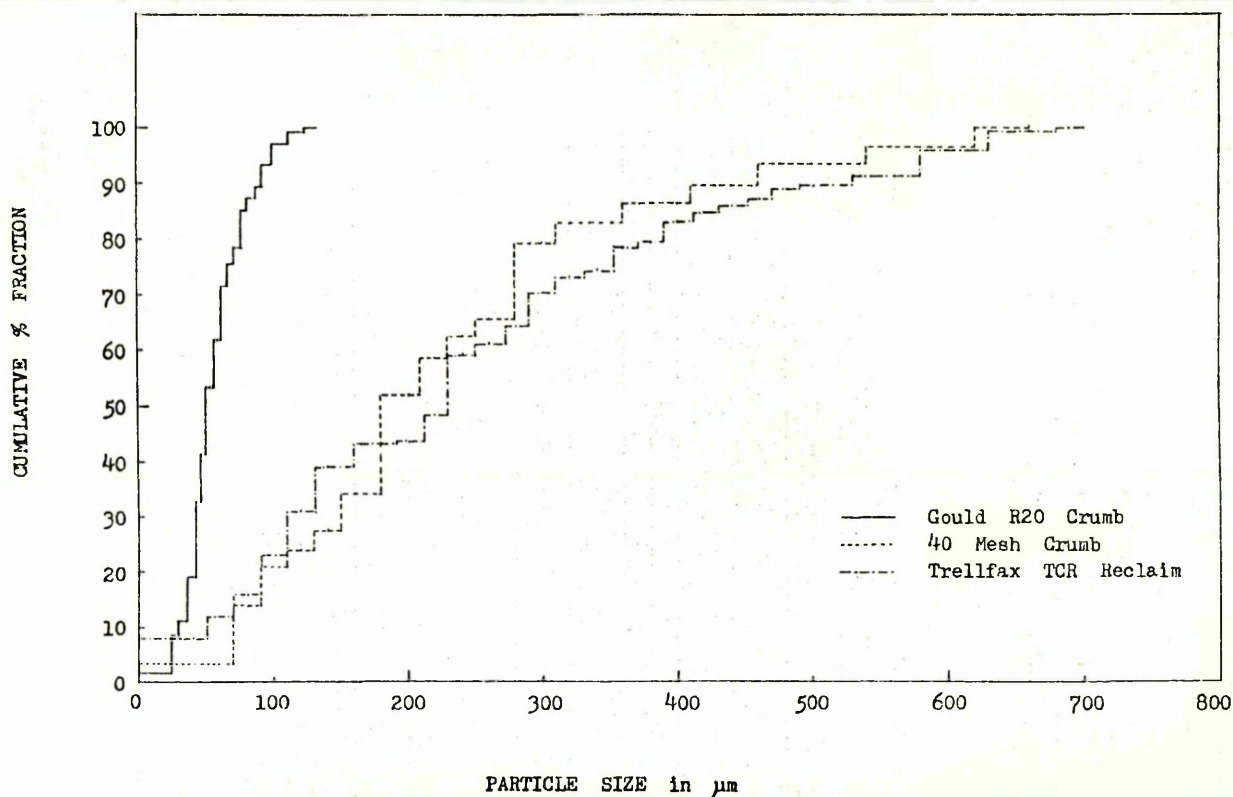


Figure 4.18 Particle size distribution for Gould R20
crumb, conventional ambient ground 40 mesh
crumb and Trellfax TCR reclaim. (Number
fractions, obtained by physically counting
the particles in the micrographs.)



Figure 4.19 Gould R20 powder

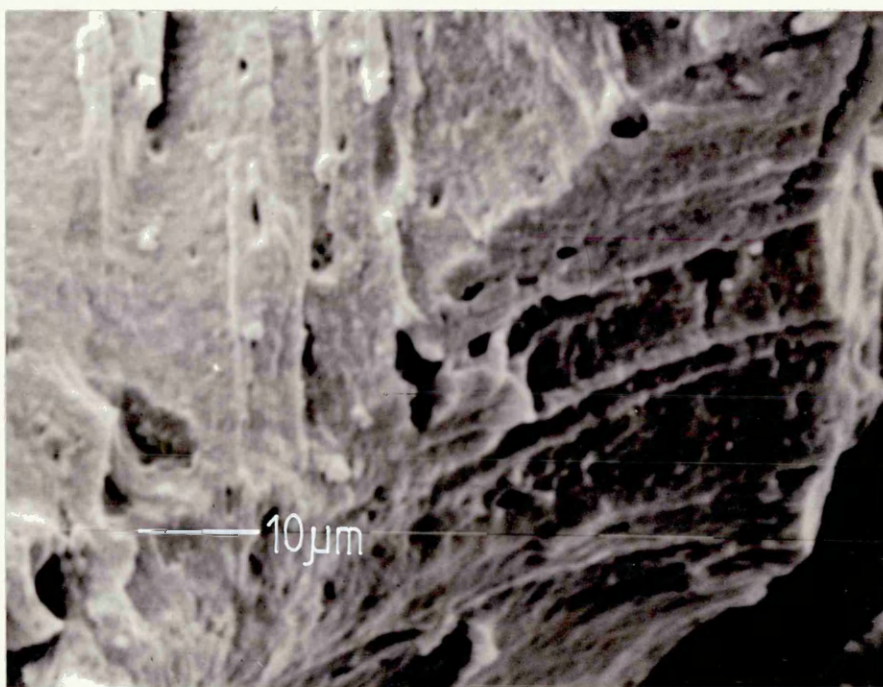


Figure 4.20 Close-up of a single particle of Gould R20 showing scaly nature of a knotty tear.

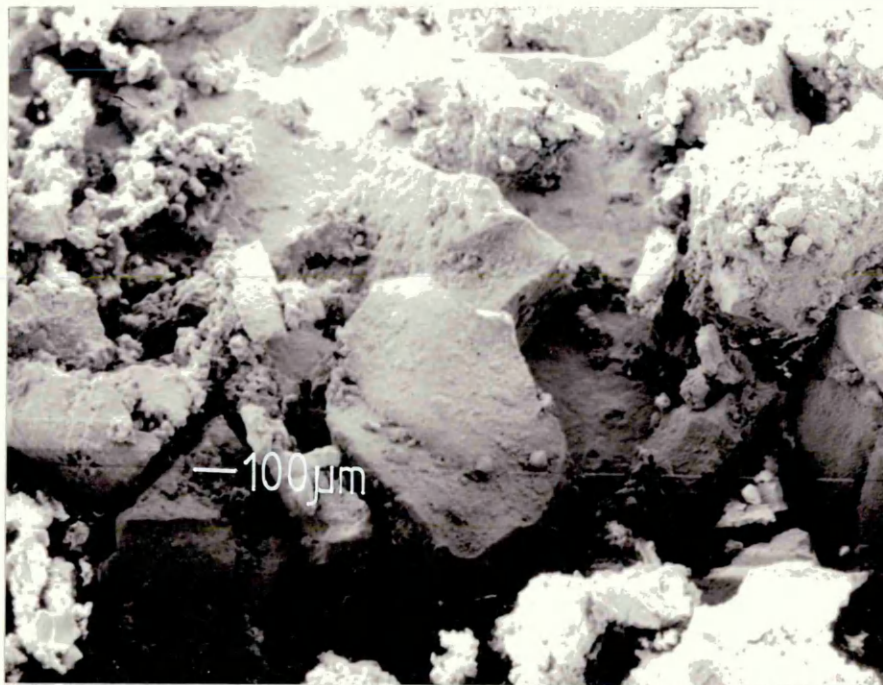


Figure 4.21 Sample of the Trellax TCR reclaim.

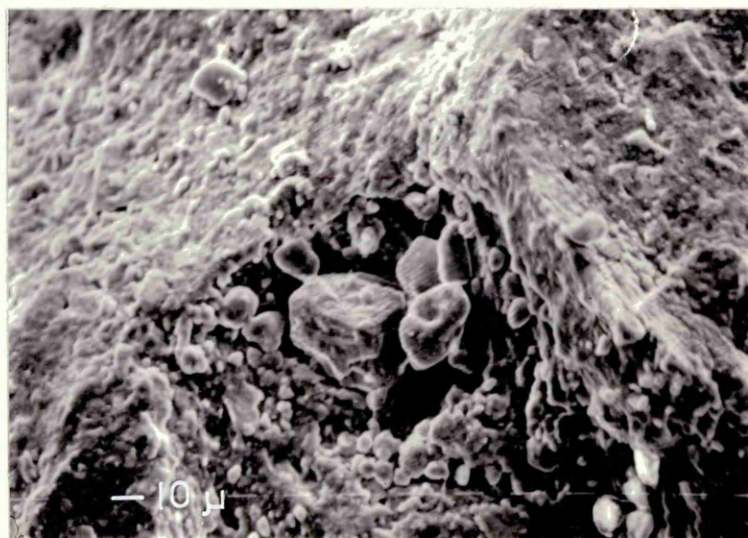


Figure 4.22 Surface close-up of a TCR reclaim particle showing surface roughness.

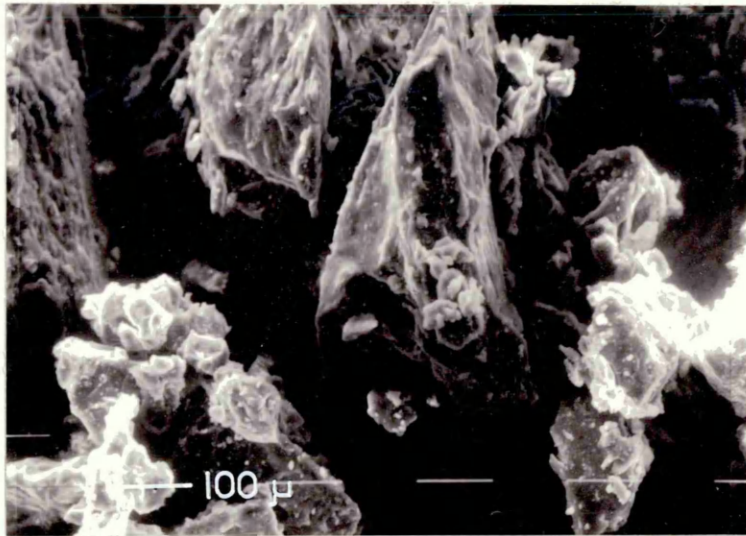


Figure 4.23 Sample of cryogenically ground crumb.

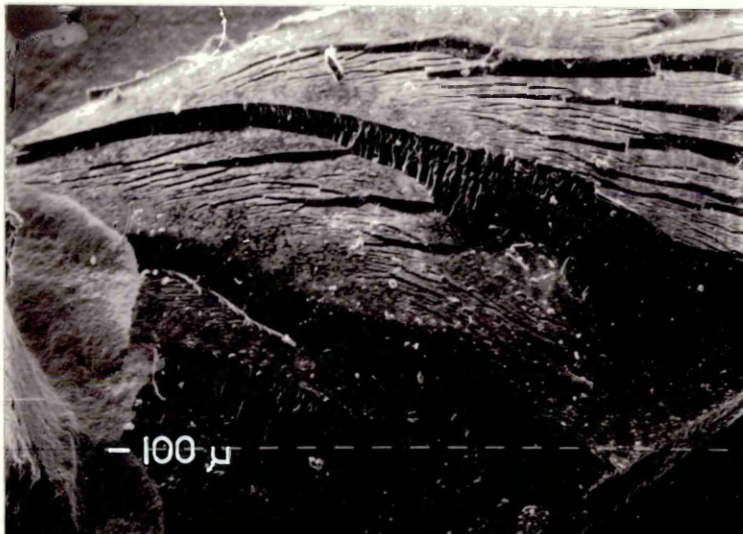


Figure 4.24 Surface close-up of a cryogenically ground particle showing brittle fracture.

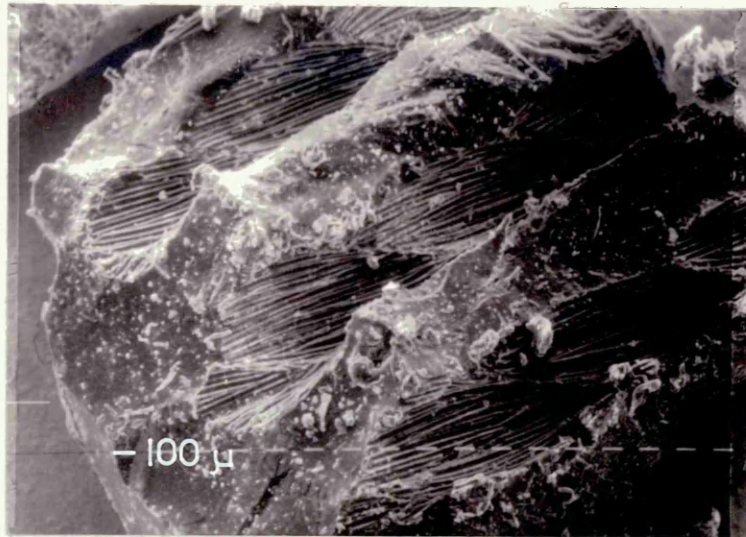


Figure 4.25 Surface close-up of a cryoground particle showing clean separation of fabric reinforcement.

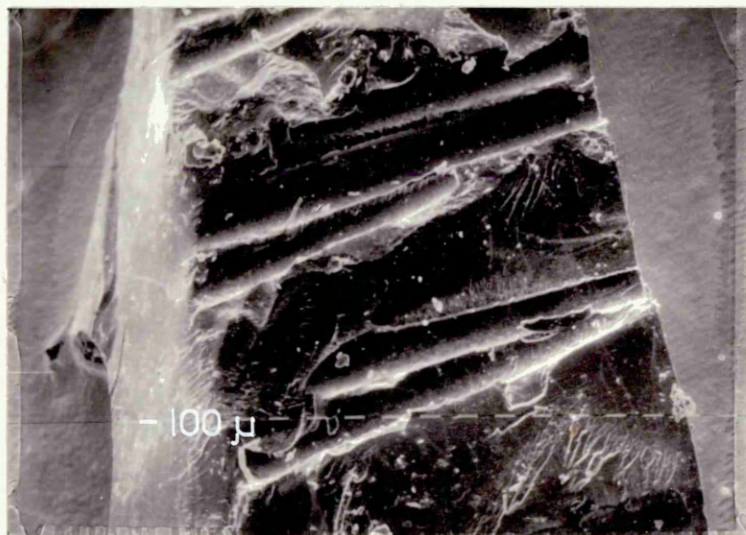


Figure 4.26 Surface close-up of cryoground particle showing clean separation of metal reinforcement.

5.1 General Considerations

It is generally accepted that the incorporation of recycled rubber into rubber compounds tends to impart inferior physical properties upon the resultant vulcanizates. In part, this has led to the rubber product manufacturers' reluctance in using recycled rubber. In order to instill confidence among rubber processors in using higher proportions of recycled rubber, and hence increase the market for recycled rubber, it is necessary to have an understanding of property relationships in rubber compound incorporating recycled rubber.

Rubber vulcanizates incorporating recycled rubber can be considered as a two-phase rubber-rubber composites. With these composites it is necessary to distinguish between (i) reclaimed rubber; and (ii) vulcanized particulate rubber crumb or powder. A reclaimed rubber forms into a rather intimate mixture with the base rubber, and these composites may be considered as a rubber-rubber blend, while vulcanized rubber particles are bound into the crosslinked matrix (matrix will be used to describe the base rubber compound hereafter). This can be clearly seen in the electron micrographs of cut surface of rubber crumb filled vulcanizates shown in Figures 6.5 through 6.8. The particulate recycled rubber may be considered as a filler.

The chemistry and physics of rubber vulcanizates are complex and some of the physical/engineering properties of rubber compounds have not yet been explained in detail. (A review of some of the important physical properties of rubber vulcanizates is presented in Appendix C.) The incorporation of vulcanized particulate rubber, and the blending of reclaimed rubber, adds another dimension to this problem. Although theoretical analysis of two, or multi-phase polymeric materials has developed considerably over the past decade, little attention has been given to rubber-rubber composites. Few systematic investigations of the properties of these material systems have been reported, and there is essentially no attempt to explain the behaviours of these materials using the theories of composites, or to identify the mechanisms responsible for such behaviours (see Appendix D for a discussion of the mechanics of composites). Although there is little data available from the literature, and many of the published experimental results appear,

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at first sight, to be conflicting, it is worthwhile to consider briefly the most relevant information given in this literature. The following discussion is based, for the most part, on material behaviour described by Burgoyne et al (14), Polyakov et al (24), Swor et al (27), TCR technique (28), Coran and Patel (153, 154) and Grebenkina et al (160).

The results of our own investigations are then considered.

The physical properties of rubber-rubber composites are governed by many independent variables. These include :

(a) the physical properties of the base, or matrix rubber, such as stiffness, strength and surface energy. These will be controlled to a large extent by the chemical composition of the base rubber, the compound recipe, the content and type of filler (usually reinforcing carbon blacks) and the vulcanizing conditions.

(b) the physical properties of the incorporated scrap rubber. In addition to the factors given in (a), the thermal, chemical and mechanical conditions the rubber experienced during its service life, and during the recycling process (eg. conventional reclaiming, ambient grinding and cryogenic grinding) will influence the physical properties of the recycled rubber. In general, the vulcanized rubber filler particles would be expected to have physical properties different to those of the crosslinked rubber matrix. This is because of possible differences in the composition and processing conditions during the first product conversion stage, and the degradation of the rubber hydrocarbon during its service life and during the recycling operation. However, degradation due to the recycling process may be small in cryogenically ground rubber crumb.

(c) the geometry of the particulate filler, such as its overall shape (eg. spherical, ellipsoidal, angular), particle size and size distribution, and the surface structure (eg. smooth or rough). The composition and surface energy of the incorporated rubber filler particles will influence the chemical bonding between filler and matrix, and the surface structure (together with surface energy) will influence the physical bonding.

(d) the compound formulation and process variables for the rubber-

rubber composite, which include the proportion of recycled rubber incorporated into the material system, the type and amount of cross-linking system (usually sulphur with accelerators), the type and amount of filler (eg. reinforcing carbon black and diluent china clay), and the cure conditions (time, temperature and pressure). The proportion of recycled rubber can be expressed in several ways : in terms of the traditional parts per hundred rubber (phr); the weight or volume fractions; or in term of the percentage of rubber hydrocarbon (RHC). Conventionally, all rubber compounding ingredients, including recycled rubber, are expressed as parts by weight per one hundred parts of the base rubber (see Appendix E for examples). Since model representations are expressed in terms of volume fraction of filler it is necessary to consider the relationship between V_{RR} (in %) and the traditional measure ϕ_{RR} (in phr).

As a simplification, it is assumed that all compounding ingredients remain within the base mix which, after vulcanization forms the matrix of the composite. (This assumption is not strictly valid because a small amount of curing agent may have diffused from the mix). It is also assumed that the compounding ingredients, apart from rubber hydrocarbon and reinforcing filler make little contribution to the matrix volume. This will result in an underestimation of the matrix volume by about 5% or less for a typical compound. Thus within a reasonable degree of accuracy, V_{RR} and ϕ_{RR} can be related as

$$V_{RR} = \frac{\frac{\phi_{RR}}{\rho_{RR}}}{\frac{100}{\rho_R} + \frac{\phi_{RF}}{\rho_{RF}} + \frac{\phi_{RR}}{\rho_{RR}}} \quad (5.1)$$

where ϕ is the traditional measure of mass fraction in phr, and ρ the material density. Subscripts R, RF and RR denote new rubber, reinforcing filler and recycled rubber respectively.

The rubber hydrocarbon content of recycled rubber has been expressed in two forms, namely (i) the RHC (by weight) of recycled rubber as a percentage of the total RHC; and (ii) the RHC of recycled rubber replacing the RHC of the virgin rubber. The curing system used will affect the state of cure of the material system.

(e) the test conditions, such as the temperature, time and rate of deformation at which testing of physical properties is carried out. The data given in the literature are essentially single point values. It is well established that the mechanical behaviour of rubbery materials can only be properly described in terms of property-temperature-time (or rate) surfaces. These surfaces allow the basic molecular processes responsible for the mechanical behaviour to be identified.

5.2 Previous Work

In previous publications, no consideration has been given to the modelling of material behaviour and only in a few cases have comments been made concerning mechanisms. Thus our review of previous work is confined to the presentation and analysis of relevant experimental results. As a starting point for discussion some single point data given in Figure 5.1 may be used. This compares the 300% tensile elastic modulus, the tensile strength and the elongation-at-break of a base rubber compound and the same compound incorporated with whole tyre reclaim (WTR), 40 mesh crumb and micromised crumb (by the Gould process, reference (19, 27)). It is seen that, in general terms, the physical properties of compounds incorporating recycled rubber are inferior to the base rubber compound, although in some circumstances the stiffness may be enhanced. This behaviour is discussed in more detail below. To facilitate this discussion, it is helpful to establish the basic material property requirements. These requirements may be arbitrarily taken to be that the physical properties of the rubber-rubber composite should be the same as that of the base rubber vulcanizate in all respects.

(a) Elastic Properties

Initial elastic modulus $(E_0)_C$, is a measure of the stiffness and hardness of the rubber vulcanizate. Since most rubber composite systems reported have purposely been designed to give a constant hardness, little information concerning $(E_0)_C$ is available. This has been done by adjusting the carbon black type and content (28), and/or the curing agent content of the base rubber mix (27). The elastic properties have usually been expressed in terms of the 100% or 300% tensile elastic moduli, $(E_{100})_C$ and $(E_{300})_C$, which depends on the shape of the stress-strain curve (see Figure C.4 of Appendix C for example), as well as $(E_0)_C$. Hence, hindering the usefulness of this modulus information.

For particulate recycled rubber composites, it has been shown that, in general, the tensile modulus at low strains decreases with increasing mass fraction of recycled rubber filler, ϕ_{RR} . However, there are exceptions to this behaviour. Peterson et al (159), for example, working with cryogenically ground rubber crumb, showed that $(E_{300})_C$ for nitrile rubber (NBR) and $(E_{100})_C$ for polychloroprene rubber (CR) incorporated into parent compound decreased with increasing ϕ_{RR} . This relationship shown in Figure 5.2 can be seen to be almost rectilinear, implying that the tensile moduli of these material systems may obey a

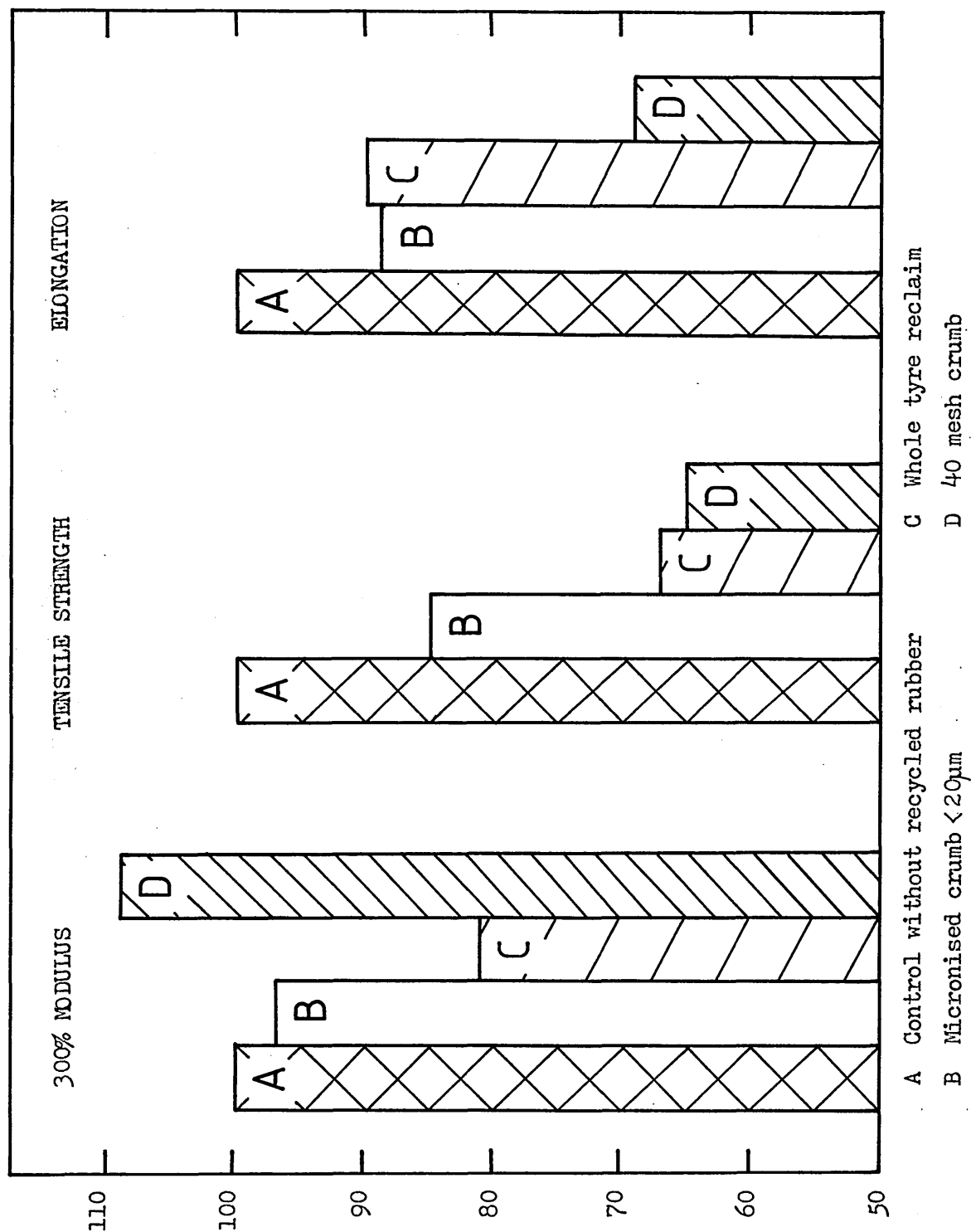


FIGURE 5.1 Single point data for a rubber compound incorporating different types of recycled rubber.
(data from Lee (109))

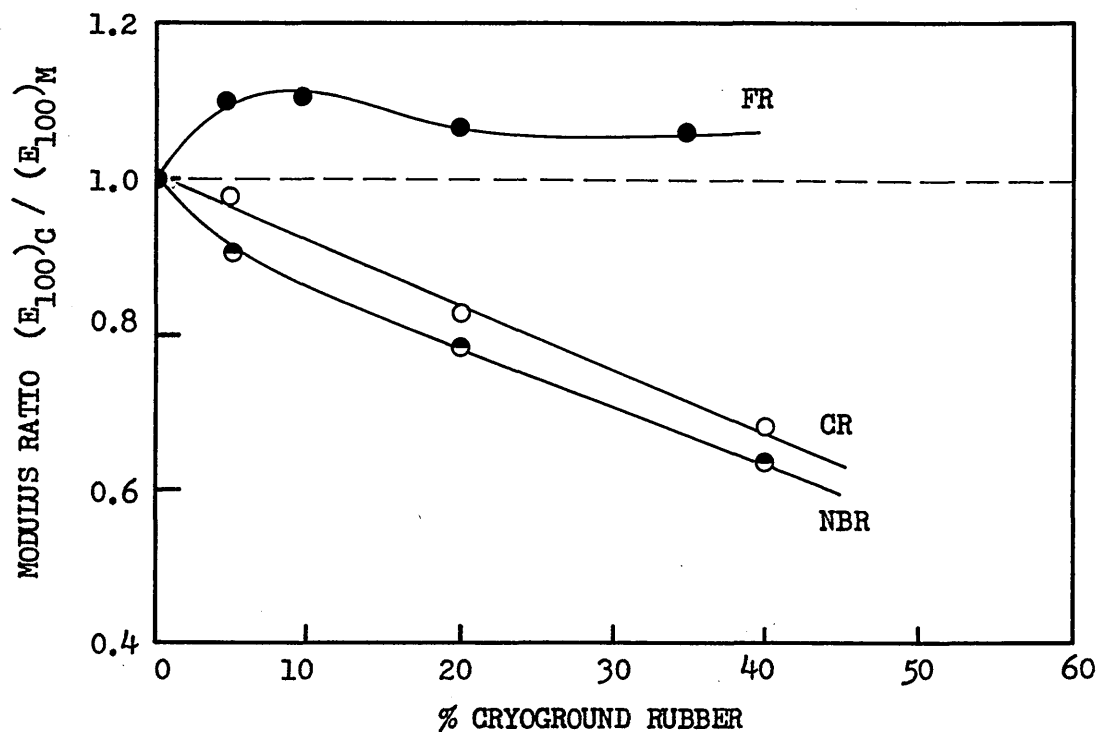


FIGURE 5.2 Variation of the Modulus Ratio as a function of the Amount of Cryoground Recycled Rubber Incorporated in the Compound.

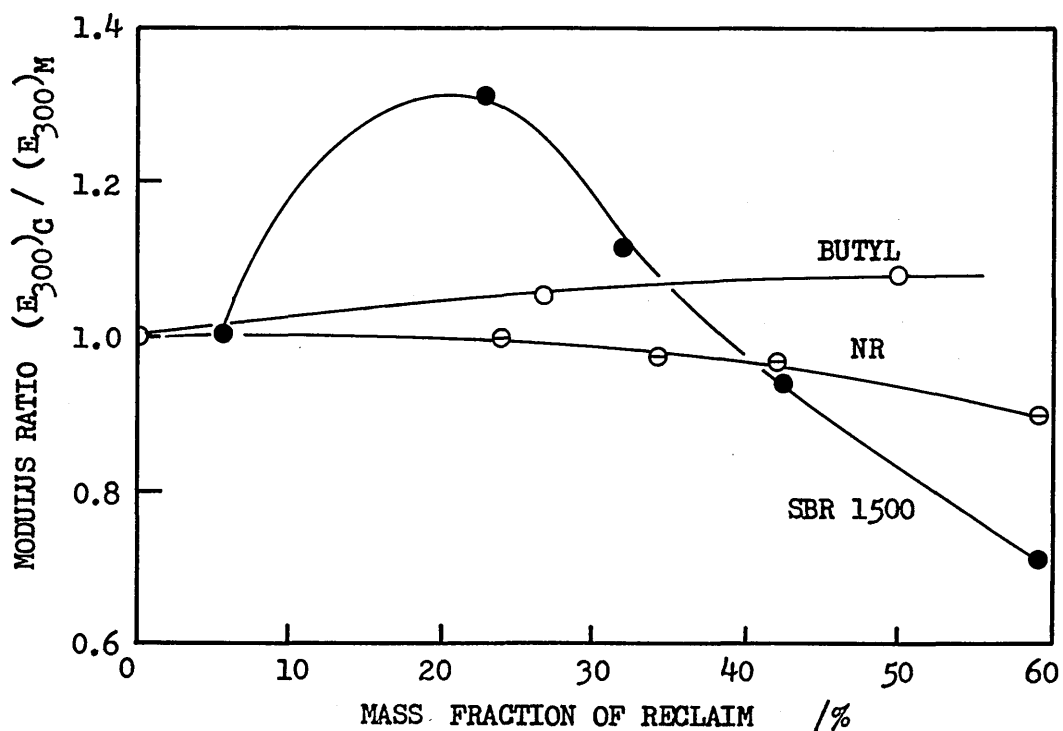


FIGURE 5.3 Variation of the Modulus Ratio as a function of the Amount of Reclaim Incorporated in the Compound.

simple law of mixtures expression. With fluorocarbon rubber (FR) composite, however, $(E_{100})_C$ initially showed a moderate increase with increasing ϕ_{RR} and then passed through a maximum value. Similar behaviour has been reported for whole tyre reclaim (WTR) incorporated into different base rubbers (158). Some of these experimental results are given in Figure 5.3.

The data given by Swor et al (27) for micronised rubber crumb derived from passenger tyre tread peels (the Gould process) incorporated in SBR 1500 based rubber compound can be examined in more detail. The curing system (3.2 phr of sulphur and 1.2 phr of CBS accelerator) was held constant while ϕ_{RR} was varied in this investigation. 90% of the micronised rubber particles had average diameters of less than 20 μm , which corresponds to ASTM 500 mesh. Data for $(E_0)_C$ and $(E_{300})_C$ for this micronised crumb composites are presented in Figure 5.4. The value of $(E_0)_C$ for the micronised crumb composites have been calculated from the hardness values (Shore A) given by the authors, assuming the Shore A hardness approximately equals IRHD and using the relationship between IRHD and E_0 given by Gent (148) (also described in Figure C.5 of Appendix C). Following from the discussion of elastic modulus and the predictions of the Kerner model given in Appendices C and D, the relationships presented in Figure 5.4 would imply that the elastic modulus of the micronised crumb particles was less than that of the rubber matrix material. It can also be seen from the Figure that the shape of the modulus ratio curve is different to that predicted by the Kerner model; the experimental data shows an increasing negative gradient, whereas the model predicts a decreasing negative gradient. Thus it would appear that the Kerner equation does not apply to this material system.

As mentioned earlier, the elastic behaviour of a rubber is often expressed in terms of the stress or the stress-strain ratio at a particular value of strain rather than the initial elastic modulus. For example, modulus at 300% elongation E_{300} is often used, where $E_{300} = \sigma_{300}/3$. Data for the micronised crumb and a WTC-SBR 1824 (158) systems, in the form of $(E_{300})_C / (E_0)_C$ ratio, is given in Figure 5.5. It can be seen that the different systems show different behaviours. According to the classical theory of rubber elasticity (49), $\sigma = (E_0/3) (\lambda - \lambda^{-2})$ where σ and E_0 have the usual meaning of stress and initial modulus, and λ is the elongation ratio. At 300% elongation, $\lambda = 4$, and hence

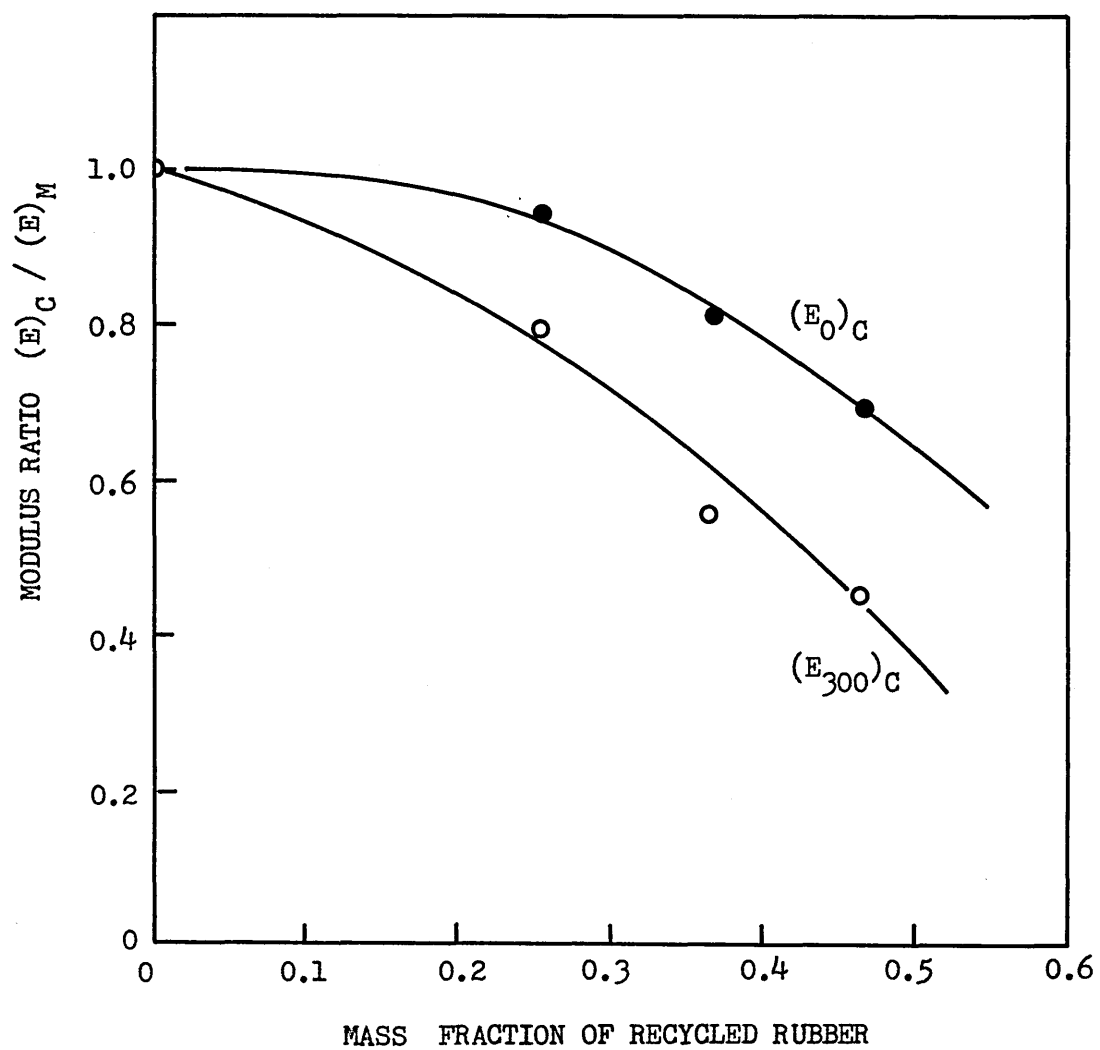


FIGURE 5.4 Variation of the Initial and 300% Elastic Modulus as a function of the Amount of micronized rubber incorporated in the compound.

$\sigma_{300} = (E_0/3)(4 - \frac{1}{16})$, and this gives E_{300}/E_0 a value of 0.44, as shown in Figure 5.5 as broken line. It is known that the Classical Theory over-estimates the stress in a rubber network at these strains (see for example Treloar (49), and Figure C.4 of Appendix C), so it is expected that practical E_{300}/E_0 values will be less than 0.44. The micronised crumb system exhibits a surprising behaviour in that the E_{300}/E_0 ratios are higher than the predictions of the Classical Theory. This may indicate that this material system has a different stress-strain behaviour from that described by the Classical rubber elasticity Theory. The study of stress-strain relationship of the 40 mesh crumb system using the classical and non-Gaussian theories of rubber elasticity is examined in a later section.

The mathematical model described and used above do not appear to be fully applicable to the rubber-rubber composite materials. Given the large number of independent variables involved, this observation is hardly surprising. The discussion below may provide a possible explanation for such modulus - ϕ_{RR} relationship. Swor et al (27) have indicated that for their sulphur cured micronised crumb containing rubber compounds, part of the compounded sulphur migrates from the rubber matrix to the particulate rubber filler during vulcanization. This has been confirmed (see Chapter Six), and it was also shown that the migration of sulphur curing agent from the matrix, as expected, increased with increasing volume fraction of recycled rubber filler. Thus, from the information given in Appendix C and D, it would be expected that the modulus of the matrix of the recycled rubber composites with constant cure system to decrease with increasing volume fraction of recycled rubber, even if the initial modulus of the recycled rubber particle is similar to that of the rubber matrix. Such structural change in the matrix has also been reported by Grebenkina et al (160).

Grebenkina and coworkers studied the distribution of sulphur using a three-layer model system consisted of a middle vulcanised layer sandwiched between two unvulcanized mix of the same compound formulation. They have shown that the diffusion of vulcanizing agent from the rubber mix into the rubber vulcanizate determines the phase structure of the material system as a whole, and consequently its properties. They have also shown that with particulated vulcanized rubber particles, the decrease in $(E_0)_C$ with increasing ϕ_{RR} could be

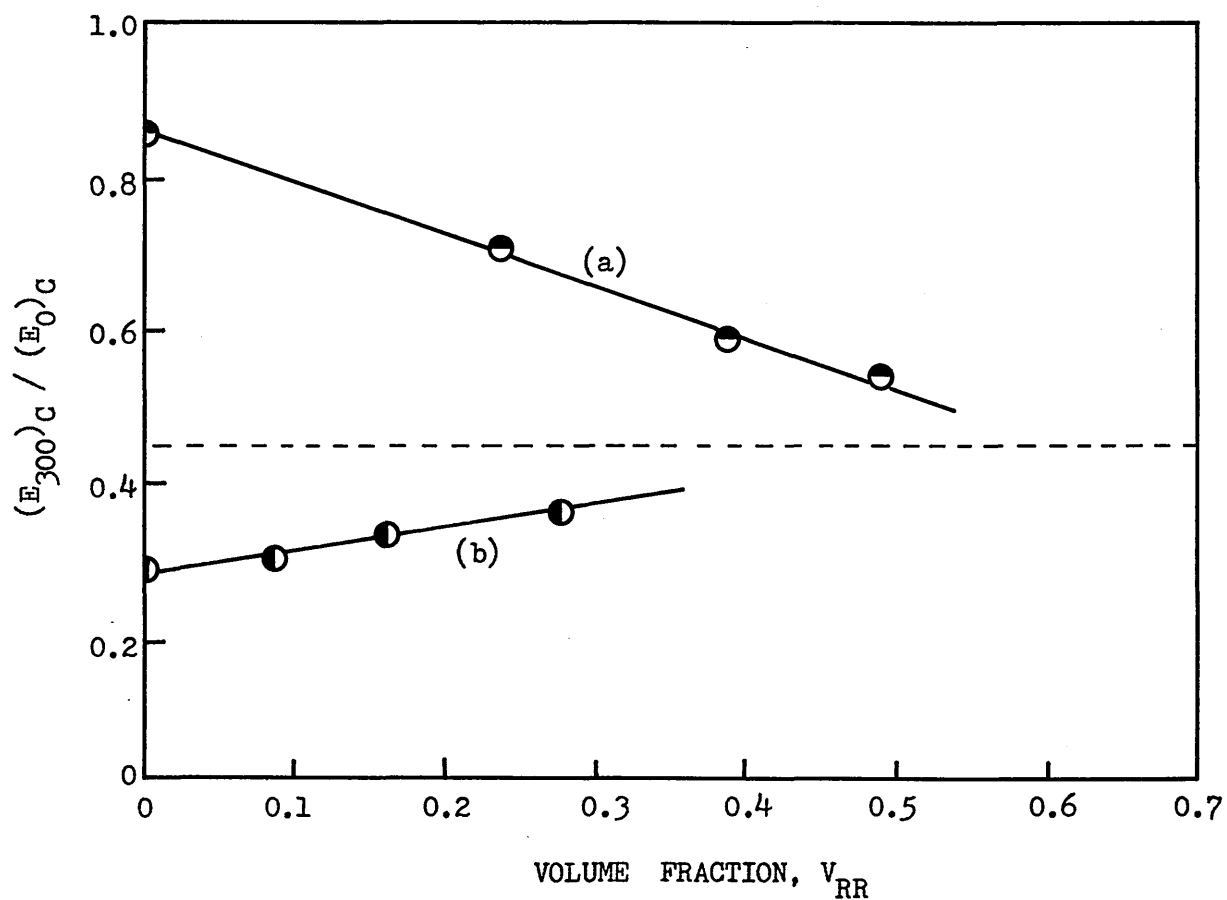


FIGURE 5.5 Variation of Modulus Ratios as a function of Volume Fraction of Recycled Rubbers. (a) Micronized crumb - SBR 1500 (data from Swor et al (27)); (b) Whole tyre reclaim - SBR 1824 (data from (158)).

explained by the same mechanism, and that the physical properties of the rubber-rubber composite could be maintained close to that of the base rubber compound provided a slow-diffusing vulcanizing agent is used.

The effect of increasing the sulphur content of the base rubber mix is, therefore, to increase crosslinking in both the matrix and the particulate rubber filler. Swor and coworkers have shown that (see Figure 5.13), with an appropriate adjustment in sulphur level, the E_{300} of the micronised crumb composite may be improved by a substantial amount.

Another measure of stiffness, from a practical point of view, is the hardness of a rubber compound which has been shown (148) to have a definite relationship with the initial modulus, E_0 . The influence of the hardness of the vulcanized rubber crumb on the elastic modulus (and hence hardness) of the rubber-rubber composite has been investigated by Polyakov et al (24) using a 70/30 butadiene - α -methylstyrene copolymer as the base rubber. Rubber crumb with different hardness values was prepared by cryogenically grinding vulcanized specimens of the base compounds incorporating varying amounts of carbon black. Different size fractions of crumb were incorporated into a standard base rubber compound with $\phi_{RR} = 0.25$. Unfortunately, the modulus/hardness of the base rubber compound was not given. However, assuming that this was 70 degrees TM-2 hardness (Russian standard which is approximately equal to Shore A scale), it is possible to plot the ratio of modulus of the composite to the modulus of the base compound, $(E_0)_C / (E_0)_m$, as a function of the parameter $\alpha = E_{RR} / E_m$. This plot is shown in Figure 5.6 for size range of 315-560 μm , together with the behaviour predicted by the Kerner model (equation D.3 of Appendix D). The agreement between the experimental data and the Kerner model may be considered to be good in view of the assumptions and approximations made.

The situation regarding elastic modulus data in recycled rubber-thermoplastic composites is slightly simpler, as there is no complication involving curing agent, and the number of independent variables involved may not be as large. Coran and Patel (153,154) have carried out detailed studies of various rubber-thermoplastic composites, and shown that the elastic properties of these material systems follow quite closely an expression based on the simple law of mixtures (given by equation D.2 in Appendix D). The unknown parameter, p , in

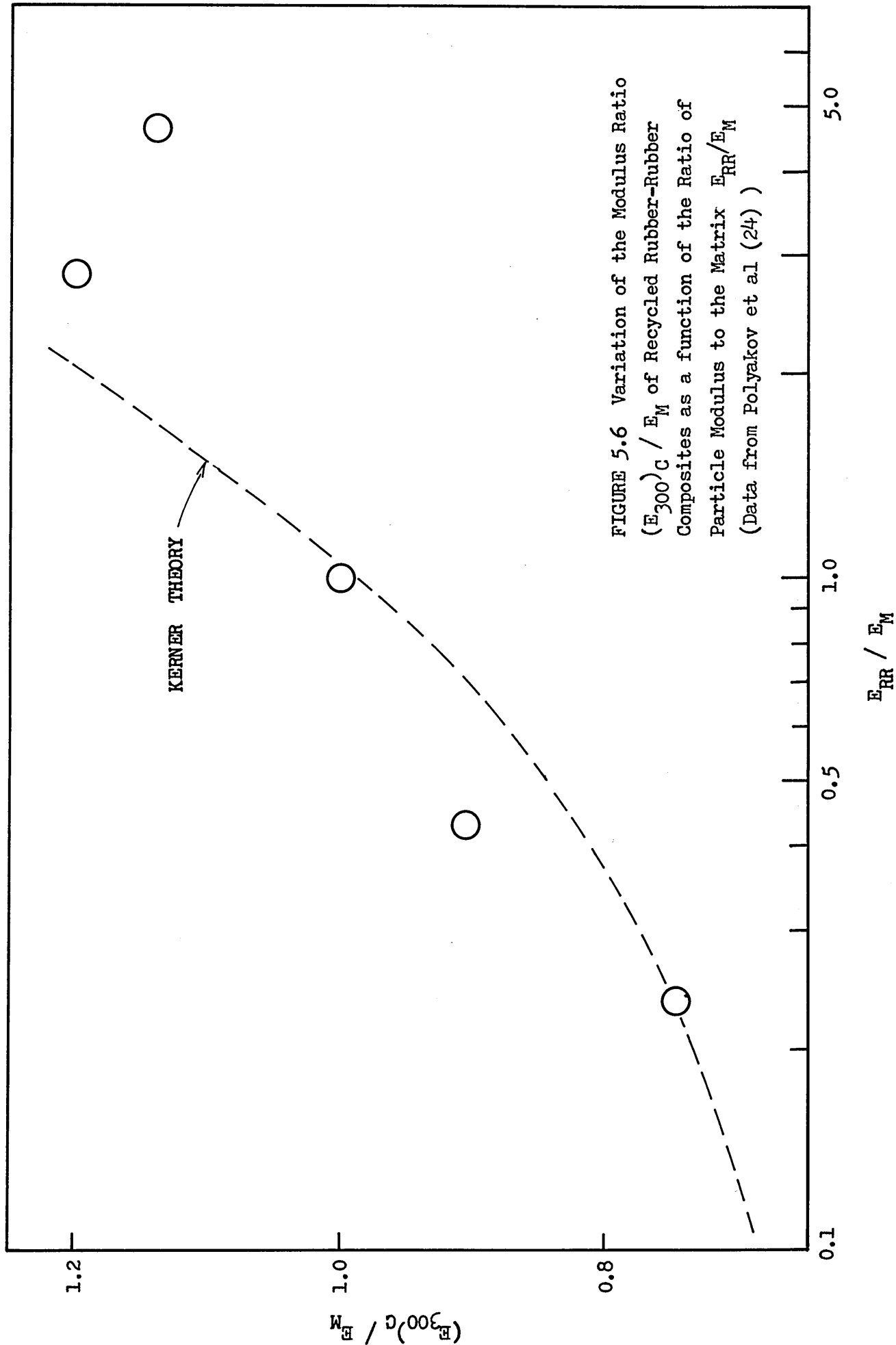


FIGURE 5.6 Variation of the Modulus Ratio $(E_{300})_C / E_M$ of Recycled Rubber-Rubber Composites as a function of the Ratio of Particle Modulus to the Matrix E_{RR} / E_M (Data from Polyakov et al (24))

this system is given by the expression :

$$p = \phi_m^n (n \phi_{RR} + 1) \quad (5.2)$$

where ϕ_m is taken to be the volume fraction of the hard thermoplastic phase, and n depends on several material factors including the detailed morphology of the thermoplastic phase such as the degree of crystallinity.

(b) Strength Properties

The strength properties of a polymeric material system can only be described in detail by means of a property-temperature-rate surface. This information is not available for recycled rubber-rubber composites. However, several of the important variables governing the strength properties, σ_B (tensile strength) and ϵ_B (elongation-at-break), have been investigated. These include the effective diameter, d_{eff} , of the recycled rubber particles, the volume fraction of the recycled rubber and the curing system.

In all cases, it has been reported that the σ_B of the composite is decreased by the incorporation of recycled rubber, and the degree of property degradation increases with ϕ_{RR} . However, the effect on ϵ_B has varied from system to system. In some cases ϵ_B was lowered, whereas in others it was enhanced. Since the size of the recycled rubber crumb plays an important role, as indicated in Appendix C, this parameter will be considered first.

(i) Effect of Recycled Rubber Crumb Particle Size

Although several theoretical models indicate that the particle size of the rubber crumb will have a profound effect on the strength properties of rubber crumb-rubber composites, only one systematic experimental investigation has been published. Burgoyne et al (14) have reported data showing the influence of a range of rubber crumb particle sizes. The material system they used consisted of recycled rubber particles of different size fractions, produced by a two stage ambient grinding process, incorporated in different amounts into a soft base rubber compound. From their data, presented in the form of $(\sigma_B)_C - \phi_{RR}$ and $\epsilon_B - \phi_{RR}$ curves for different mesh size ranges, they found in their case that both $(\sigma_B)_C$ and ϵ_B decreased with increasing ϕ_{RR} . These workers made little attempt to analyse the data obtained.

An appropriate analysis, based on Gent model for strength properties of vulcanizate (see Appendix C) is as follows :

By taking cross-sections through their curves of $(\sigma_B)_C - \phi_{RR}$, it is possible to obtain an indication of the influence of particle size on σ_B . Curves generated in this way for $\phi_{RR}=2.5\%$ and $\phi_{RR}=10\%$ are shown in Figure 5.7. The particle size range, which is represented by the horizontal bars on the graph, was estimated by assuming that these workers employed ASTM mesh size. It can be seen that the tensile strength, σ_B , increased with decreasing particle size, and σ_B approached that of an unfilled compound as $d_{eff} \rightarrow 0$.

They also reported data for a particulate clay filler with mesh size of less than 325 ($d_{eff} < 40 \mu m$). By extrapolating the appropriate curves, it is seen that the strength of the clay-filled system was much less than that of a recycled rubber filled system of equivalent particle size. In fact, the σ_B for the clay filler of $d_{eff} < 40 \mu m$ correspond to values for particulate recycled rubber of $d_{eff} \approx 140 \mu m$. This implies that with recycled rubber, the degree of bonding between particles and matrix was larger than that for the clay-filled system. The chemical incompatibility between the inorganic clay particles and the essentially organic rubber matrix may have played a significant role in this case.

These data are given for rubber crumb particles of particular size fractions; within each fraction there was a distribution of particle size. Hence, they cannot be analysed in detail using theories of composite material. However, some insight into the mechanism which may be responsible for the observed behaviour can be obtained using concepts described in Appendix C and D.

Assuming there is partial bonding, it may be expected that the amount of coupling between the recycled rubber particles and the rubber matrix would increase with increasing interfacial area (72). That is, the amount of property loss should decrease in proportion to the ratio of the surface area to volume, A/V , of the particles. For spherical particles of uniform size :

$$\frac{A}{V} = \frac{6}{d_{eff}}$$

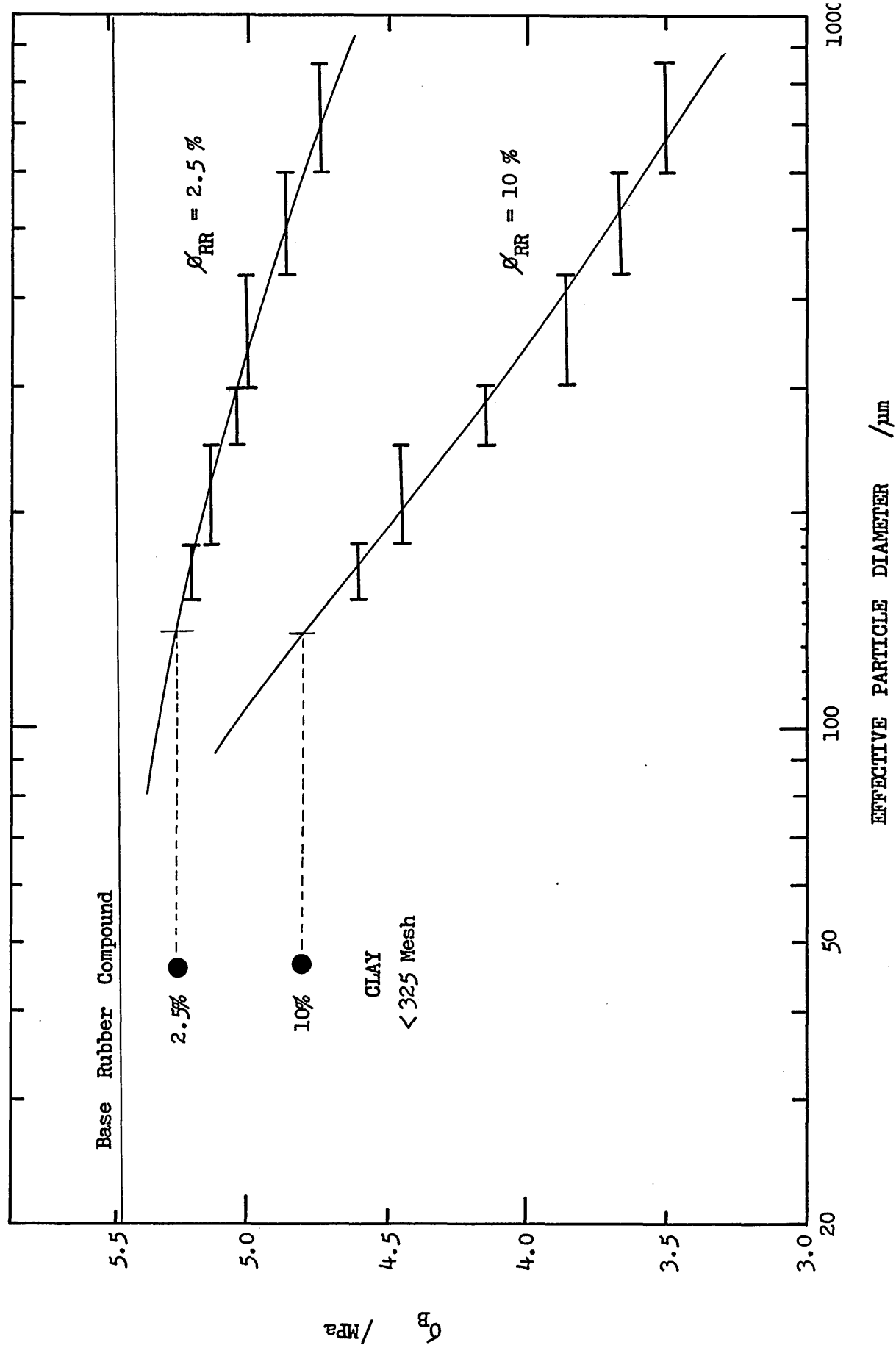


FIGURE 5.7 Variation of the Tensile Strength as a function of d_{eff} . (based on data from Burgoyne et al(1)

Therefore, it may be expected that the strength ratio of the composite, $(\sigma_B)_C / (\sigma_B)_m$, to increase in proportion to $1/d_{eff}$. Some of the data given by Burgoyne et al is shown in Figure 5.8. It is seen that a curvilinear relationship is obtained (The symbols x on the graphs do not represent actual data point but are co-ordinates taken from their $(\sigma_B)_C - \phi_{RR}$ curves).

Gent has modelled the tensile strength of rubber vulcanizates in terms of the tear energy, initial modulus and flaw size. This expression has been applied to multi-phase systems, such as polymer foams and filled polymers (153,154,200), by equating the particle size, d_{eff} , to the flaw size, C (see equation C.7 in Appendix C). Assuming that the properties of the recycled rubber in the composites are the same as those of the base unfilled rubber, and that the inherent flaw size in the base material is C_m , it can be shown from equation C.7 that

$$\frac{(\sigma_B)_C}{(\sigma_B)_m} = \left[\frac{T_C(E_0)_C}{T_m(E_0)_m} \right]^{\frac{1}{2}} \left[\frac{C_m}{(d_{eff} + C_m)} \right]^{\frac{1}{2}} \quad (5.3)$$

where T is the tear energy, and notations and subscripts have their usual meaning. Assuming that other factors remain constant, for a particular matrix rubber equation 5.3 predicts that the strength ratio should increase in proportion to $(d_{eff} + C_m)^{-\frac{1}{2}}$, where C_m typically would have a value of about $20 \mu m$ (133,150). Coran and Patel (153) showed that the strength of their rubber-thermoplastic composites manufactured using the dynamic vulcanization technique follow this proportionality quite well. The value of C_m for their thermoplastic matrix being $5.5 \mu m$.

The strength ratio of Burgoyne et al (14) is plotted as a function of $(d_{eff} + C_m)^{-\frac{1}{2}}$ in Figure 5.9, taking C_m value of $20 \mu m$. It is seen that a better straight line relationship is obtained than when using $1/d_{eff}$ as the independent variable, Figure 5.8. It is also seen the gradient of the lines is a function of the volume fraction of the incorporated recycled rubber, the gradient increases with increasing ϕ_{RR} . The relationship is shown in Figure 5.10. This could be explained in terms of variations in the values of T_C and $(E_0)_C$ with ϕ_{RR} . As demonstrated by the 40 mesh crumb system (see Figure 5.19) with a relatively soft matrix rubber, $(E_0)_C$ increases with increasing ϕ_{RR} . It is, therefore,

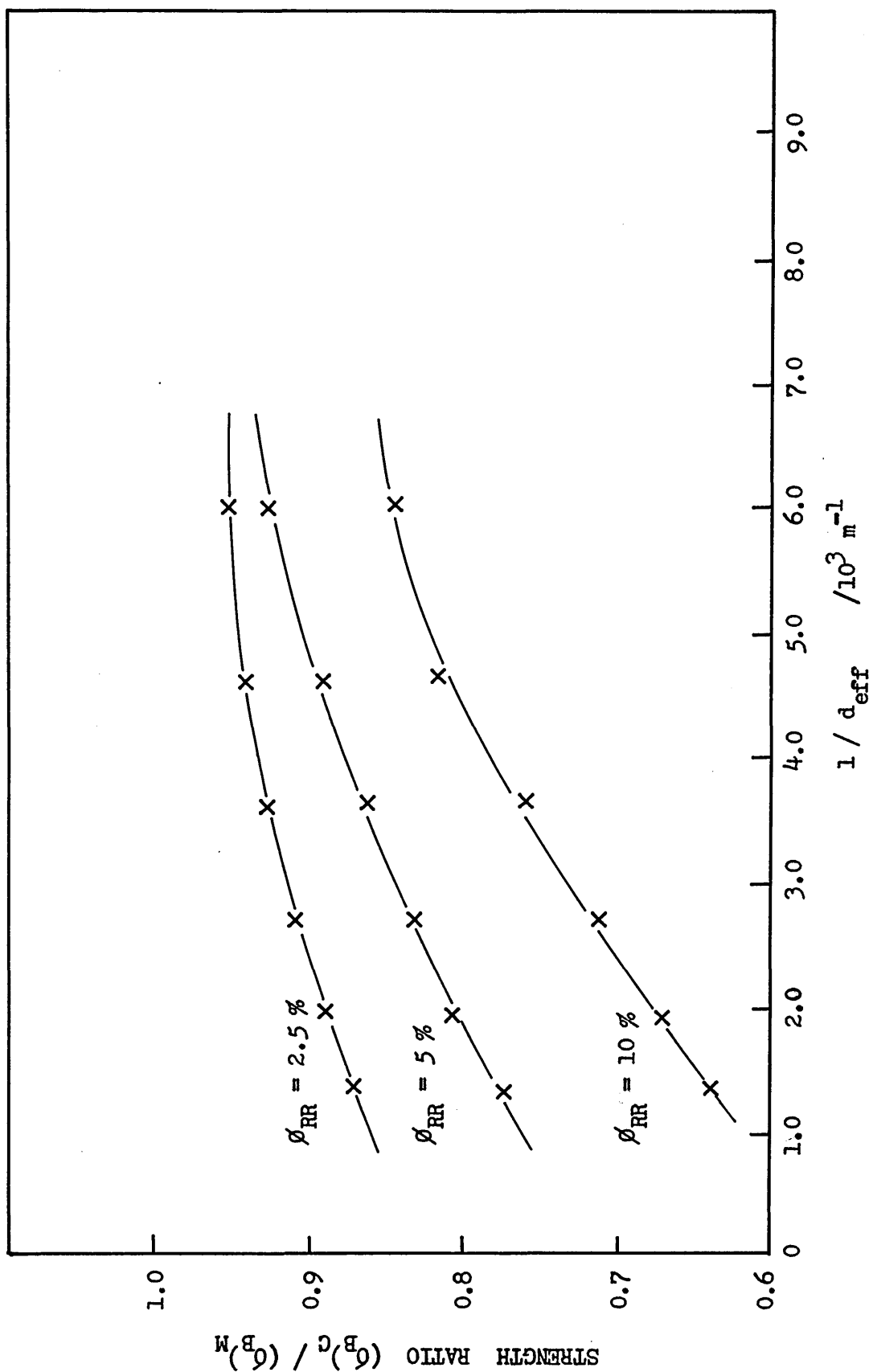


FIGURE 5.8 Variation of the Strength Ratio as a function of the Reciprocal of the Effective Diameter of the particles, d_{eff} . (Data from Burgoyne et al (14))

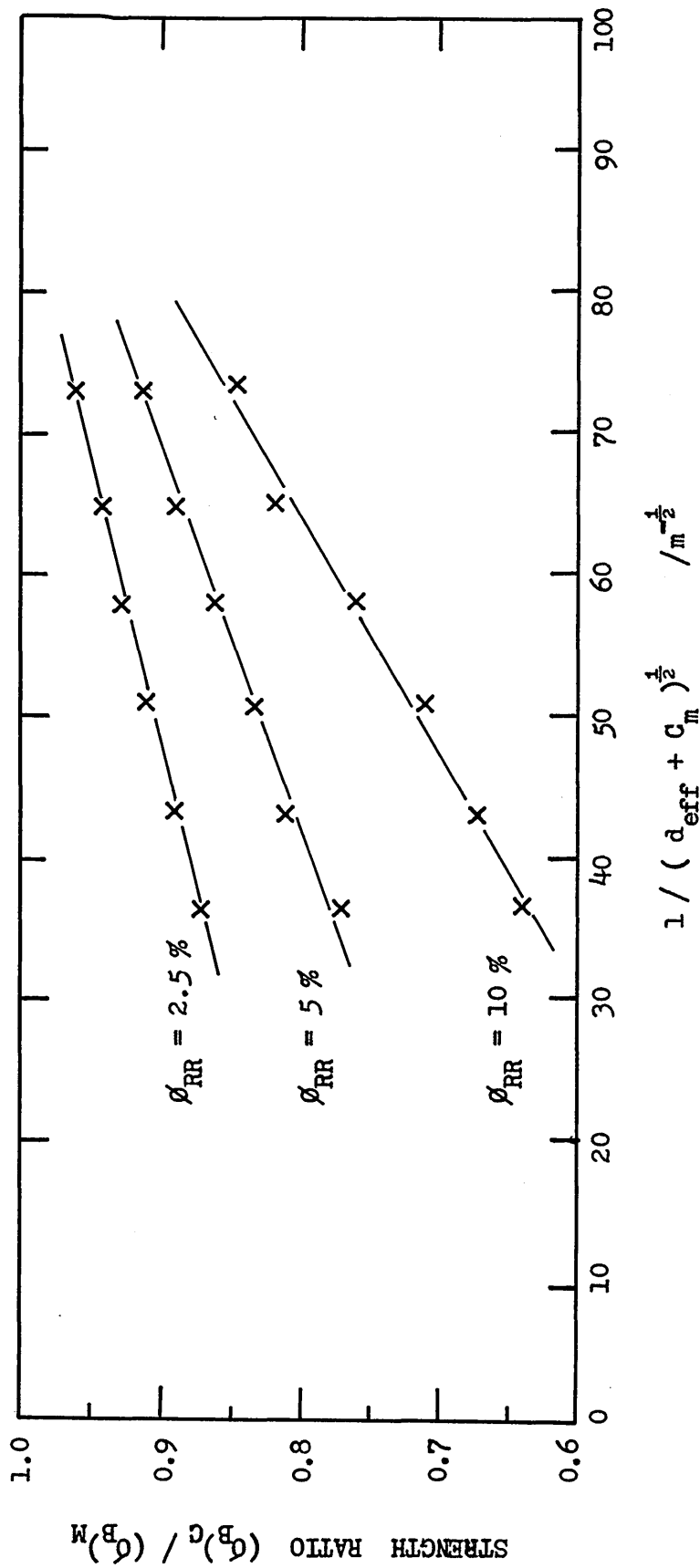


FIGURE 5.9 Variation of the Strength Ratio as a function of $(d_{\text{eff}} + C_m)^{-\frac{1}{2}}$ with $C_m = 20\mu\text{m}$
 (Data from Burgoyne et al (14))

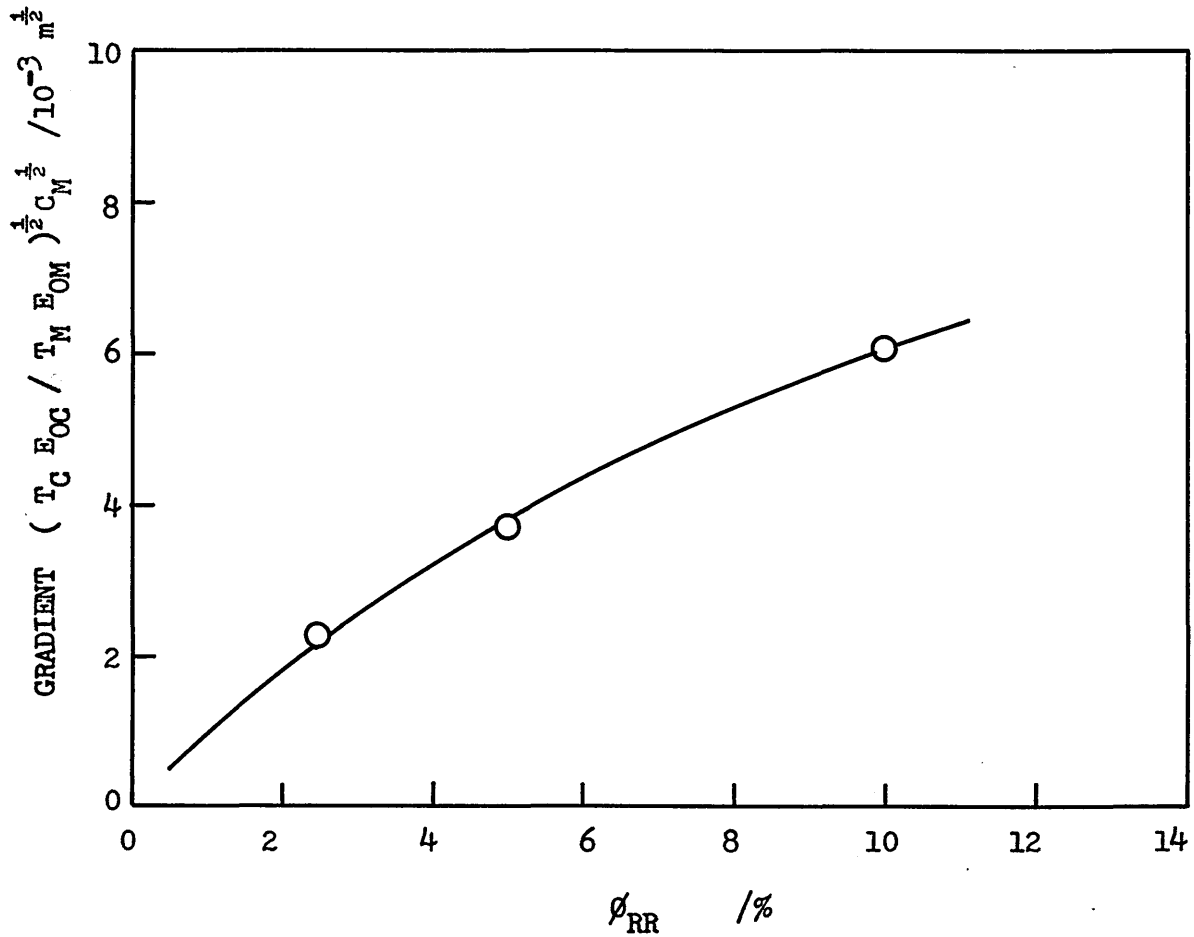


FIGURE 5.10 Variation of Gradient of $(\sigma_B)_C / (\sigma_B)_M$ vs $(d_{eff} + C_M)^{-\frac{1}{2}}$
 Plots as a function of ϕ_{RR} .
 (Original data from Burgoyne et al (14))

quite likely that, in this case, $(E_0)_C$ increased with increasing ϕ_{RR} . It has also been shown that the incorporation of rubber particles (28) at low level of addition and rigid particles (201) can lead to an enhancement of the tear strength of the composite. (As shown in Appendix C, tear strength is directly related to tear energy, T_C). The enhancement of tear energy is apparently caused by the deviation of the tear path from a straight line when a filler particle is encountered. Burgoyne has shown that the tear strength of their material system was in fact increased slightly with the addition of recycled rubber crumb.

Although the straight line relationship is in accordance with the Gent model, the full implications of this type of analysis are not fully understood. For example, the lines (in Figure 5.9) would not pass through the origin of coordinates (as found for example by Coran and Patel (153) whose straight line approached approximately to the origin), and they would not intersect at a point which corresponds to $d_{eff} = 0$, (or $(d_{eff} + C_m)^{-\frac{1}{2}} = 224 \text{ m}^{-\frac{1}{2}}$), at $(\sigma_B)_C / (\sigma_B)_m = 1.0$. Also, from Figure 5.10, it appears that the gradient decreases monotonically with ϕ_{RR} and passes through the origin. This indicates that for $\phi_{RR} = 0$ a line of zero gradient, parallel to the $(d_{eff} + C_m)^{-\frac{1}{2}}$ axis, passing through $(\sigma_B)_C / (\sigma_B)_m = 1.0$ should be obtained, as would be expected intuitively. Thus, the strength behaviours of recycled rubber-rubber composites are more complex than for rubber-thermoplastics composites. One factor which probably gave rise to such complication is the redistribution of vulcanizing agent among the matrix and the filler particles post mixing and during the cure. This is considered in some detail in the following Chapter.

(ii) Effect of Vulcanization System

The influence of sulphur content of the base rubber compound on the tensile strength of composites incorporating micronised rubber crumb has been investigated by Swor et al (27). Their results, reproduced in Figure 5.11, showed that the tensile strength of the base rubber compound and the composites initially increased with increasing sulphur content but passed through a maximum. This behaviour is typical of rubber vulcanizates (see Figure C.7) as the crosslink density increases with increasing loading of curing agent. It is also seen that the sulphur content for optimum strength properties increased with ϕ_{RR} . They concluded that the curative level adjustments are necessary to

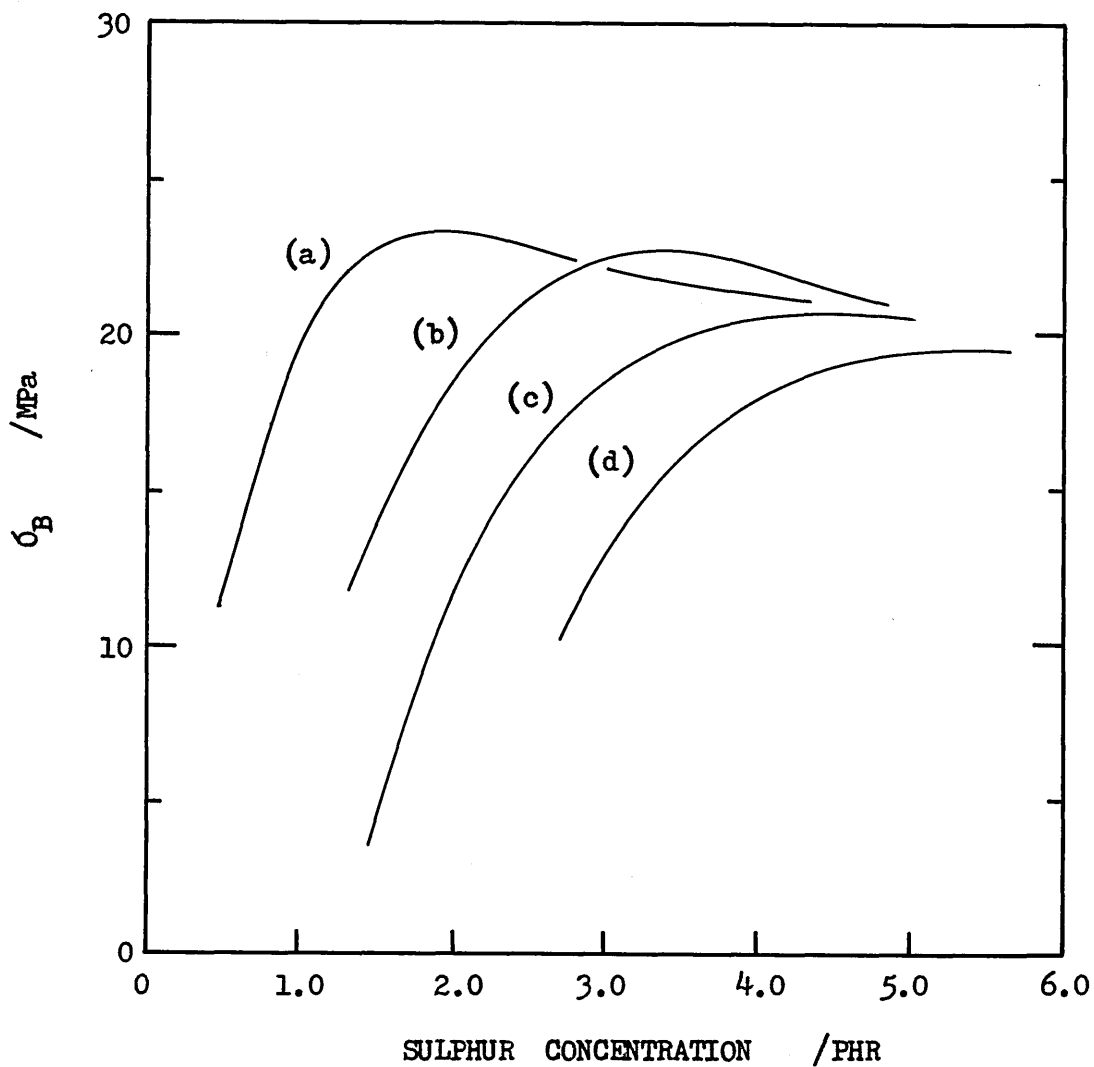


FIGURE 5.11 Variation of the Tensile Strength of Compounds Incorporating different amounts of micronized crumb as a function of the Sulphur Content of the Rubber Mix (from Swor et al (27)).
 (a) Base rubber compound; (b) $\phi_{RR} = 50$ PHR; (c) $\phi_{RR} = 100$ PHR; and (d) $\phi_{RR} = 150$ PHR.

achieve optimum strength properties in recycled rubber filled rubber composites. Their results for micronised rubber crumb show that when this is done (the levels of all curatives in the vulcaization system i.e. sulphur, accelerators, zinc oxide and stearic acid have been increased), the property loss is relatively small (see Figure 5.13).

(iii) Effect of Volume Fraction of Recycled Rubber Filler

The volume fraction of recycled rubber filler incorporated into a rubber compound is probably the most widely investigated variable. The majority of the experimental data indicate that both the tensile strength, $(\sigma_B)_C$, and elongation-at-break, ϵ_B , decrease with increasing fraction of filler, ϕ_{RR} . However, because of the multitude of independent variables within the material system, such as the type of matrix rubber, properties of the recycled rubber crumb, curing system and conditions, and reinforcing filler content, the detailed behaviour varies from system to system. One exception is the SBR 1500 based systems which has shown an increased tensile strength with ϕ_{RR} (to a small ϕ_{RR} value in some cases; eg. (27) and WT crumb systems investigated by us). Some typical data taken from the literature is given in Figure 5.12, which shows the ratio of the tensile strength of the composite to that of the base rubber compound, $(\sigma_B)_C / (\sigma_B)_m$, as a function of the amount of recycled rubber, expressed in terms of mass fraction of the total compound (including compounding ingredients other than rubber hydrocarbon).

The data are for four material systems : micronised rubber crumb (Gould process) incorporated into SBR 1500 based compound with constant cure system and conditions (27); TCR reclaim (Trellfax process) incorporated into a SBR 1500/1712 based compound with constant cure system but with carbon black level adjusted with ϕ_{RR} to give a constant hardness (28); whole tyre reclaim (WTR) incorporated into SBR 1712 based compound with sulphur and carbon black levels adjusted with ϕ_{RR} (158); and cryogenically ground nitrile rubber (NBR) incorporated into its parent compound with constant cure system.

As a basis for discussion, the mathematical expression for the tensile strength of dewetting systems given by the simple law of mixtures, equation D.4 of Appendix D, may be considered first. Assuming that the ultimate properties of the rubber filler are similar to those of the rubber matrix, i.e. $(\hat{\sigma}_B)_m \doteq (\sigma_B)_m$, then equation D.4 may be written

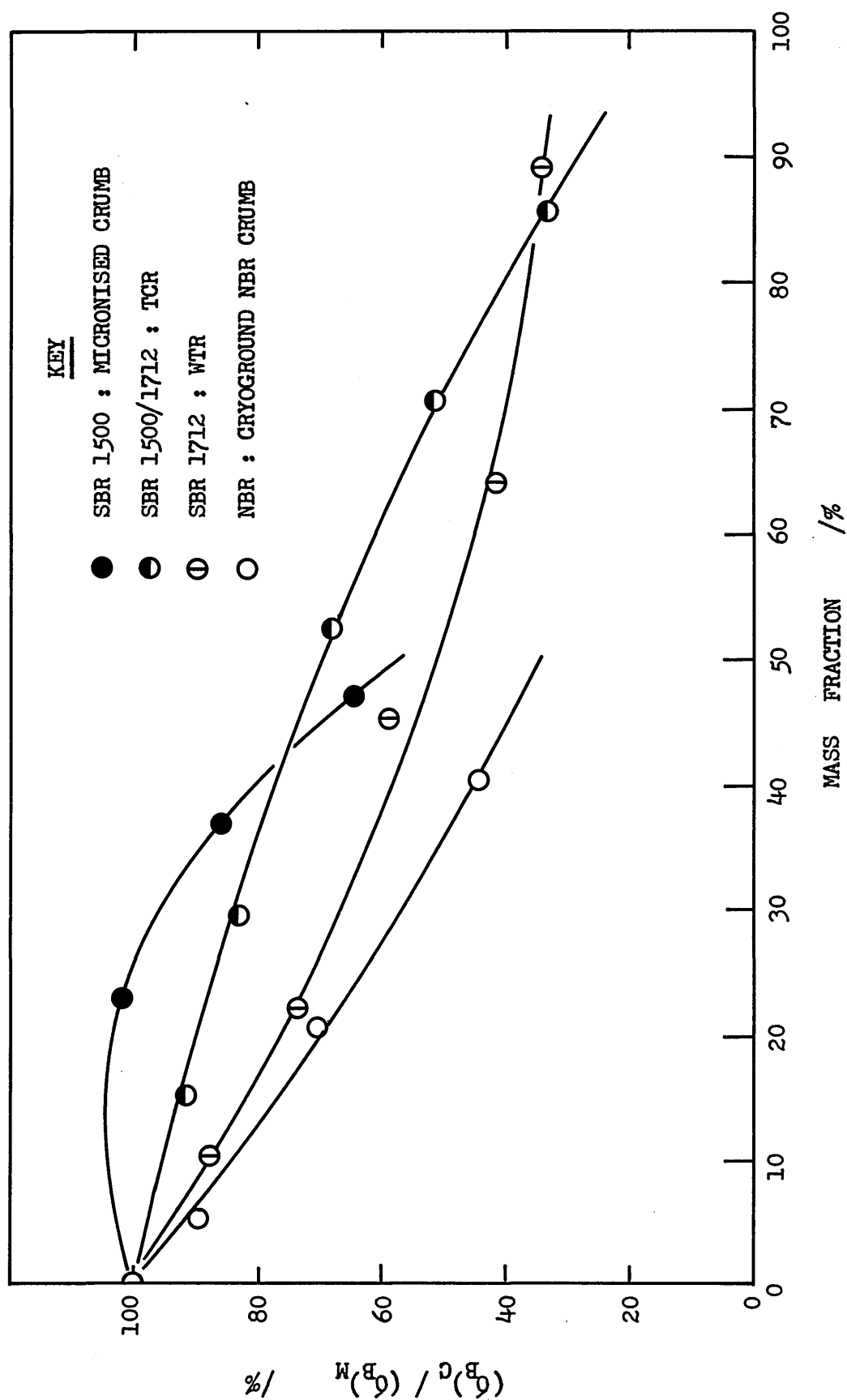


FIGURE 5.12 Variation of the Strength Ratio as a function of the mass Fraction of Recycled Rubber Incorporated into different compounds.

approximately as

$$\frac{(\sigma_B)_C}{(\sigma_B)_m} = 1 - \phi_{RR} \quad (5.4)$$

Thus, as a first approximation, the strength ratio of dewetting system should decrease in proportion to ϕ_{RR} , and $(\sigma_B)_C / (\sigma_B)_m \rightarrow 0$ as $\phi_{RR} \rightarrow 1$. The data in Figure 5.12 shows that, in general, this is not the case, although the cryoground NBR system shows fair agreement with this expression.

The elongation-at-break data of the WTC-SBR 1500 composites presented in Figure 5.27 for different sulphur loading levels of the matrix compounds, shows that, in general, the incorporation of recycled rubber crumb decreases ϵ_B , and that ϵ_B passes through a maximum value with increasing ϕ_{RR} . However, ϵ_B of a recycled rubber-rubber composite does not always decrease with recycled rubber incorporation. This is shown for the micronised crumb system in Figure 5.13, together with other physical property data for this material system. Optimised property data for the micronised crumb system, by adjusting curatives levels in the vulcanizing system, is also included. It is seen that, with curatives adjustment, the strength properties and hardness of the system were relatively closer to those of the base rubber compound, in spite of a higher ϕ_{RR} . Thus, it can be concluded that the strength loss for recycled rubber filled composites with constant cure system shown in Figure 5.12 can be attributed partly to the redistribution of curatives among the phases of the recycled rubber-rubber composites.

Only in one case has material property data been given which may be taken as representative of the strength properties, $(\sigma_B)_{RR}$, of the recycled rubber. This is for TCR recycled rubber (Trellfax process) incorporated into natural rubber (NR) and SBR based compounds (28). In these systems, the level of curing agent remained the same, but the carbon black filler content was adjusted with ϕ_{RR} so as to maintain a constant hardness of 62 degrees IRHD. In this work, the amount of recycled rubber, ϕ_{RR} , was expressed as a weight fraction of rubber hydrocarbon of the base rubber compound replaced by the rubber hydrocarbon (RHC) of the recycled rubber. (It was assumed that the recycled rubber contained 40% by weight of RHC) Thus, the total RHC

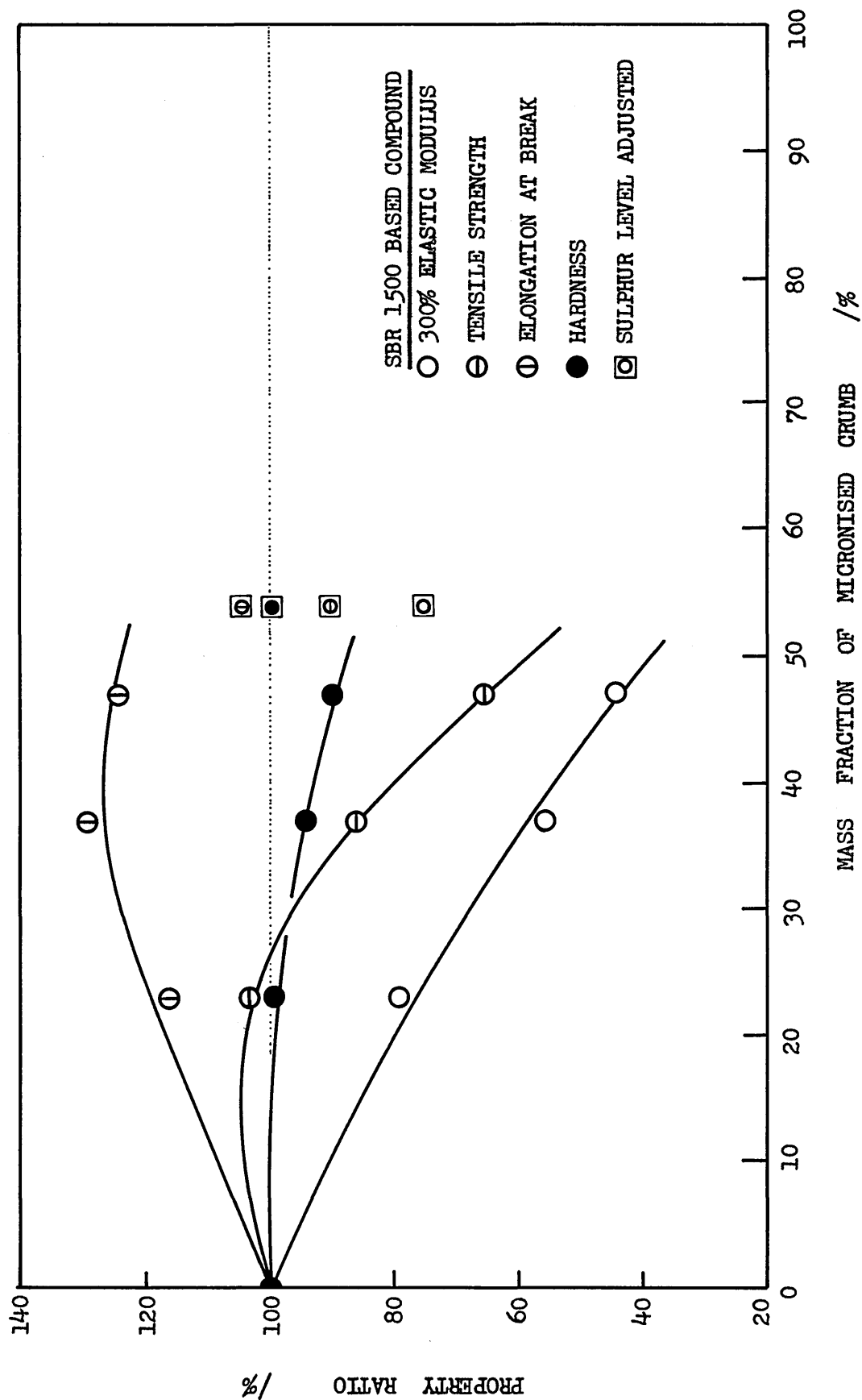


FIGURE 5.13 Variation of the Property Ratios as a function of Mass Fraction of Micronized Crumb Incorporated into a SBR 1500 based compound. (Data from Swor et al (27))

content of all the systems remained the same for all levels of ϕ_{RR} . In effect, this is equivalent to vulcanizing system adjustments. The data is given in Figure 5.14. It can be seen that when ϕ_{RR} is expressed in this way, a straight line relationship between $(\sigma_B)_C$ and ϕ_{RR} is obtained. This can be compared with the curvilinear relationship obtained when using the amount of recycled rubber expressed as weight fraction of the total compound as the independent variable shown in Figure 5.12.

Although no attempt was made in the original article to model the behaviour, the data of Figure 5.14 can be fitted well by a linear relationship based on the simple law of mixtures described by equation D.7. Expressed in terms of parameters appropriate to a recycled rubber-rubber system, this can be written as

$$(\sigma_B)_C = R \phi_{RR} (\sigma_B)_{RR} + (1 - \phi_{RR}) (\sigma_B)_m \quad (5.5)$$

where in this case, ϕ_{RR} represents the **amount** of TCR expressed as a **mass** fraction (of TCR RHC) of the total RHC in the compound, and the parameter R is a measure of efficiency of stress transfer through the particle-matrix interfacial region. It depends primarily on the integrity of the bonding between particulate recycled rubber filler and the rubber matrix. R varies from a value of 1, for a perfect bonding system, to 0, for a dewetting system. In the TCR filled system, Figure 5.14, R is observed to be unity, suggesting that it is a perfect bonding system. The fact that the TCR filled systems have a negative gradient is probably because in this system, $(\sigma_B)_m > (\sigma_B)_{RR}$.

Although equation 5.5 may not have a sound theoretical basis, it does give a good representation of the strength properties of these recycled rubber-rubber composite systems, and indicates that a better understanding of the physical property data of recycled rubber composites may be obtained if the recycled rubber content is expressed as the proportion of RHC.

(c) Tear Resistance

Bueche (149) has stated that it is not the tear process that is intrinsically complicated, but the complication is due to the several variables which govern the process. There are also many different types of tear behaviour. Although each of the variables governing the tear process in homogeneous rubber is reasonably well understood, the combination

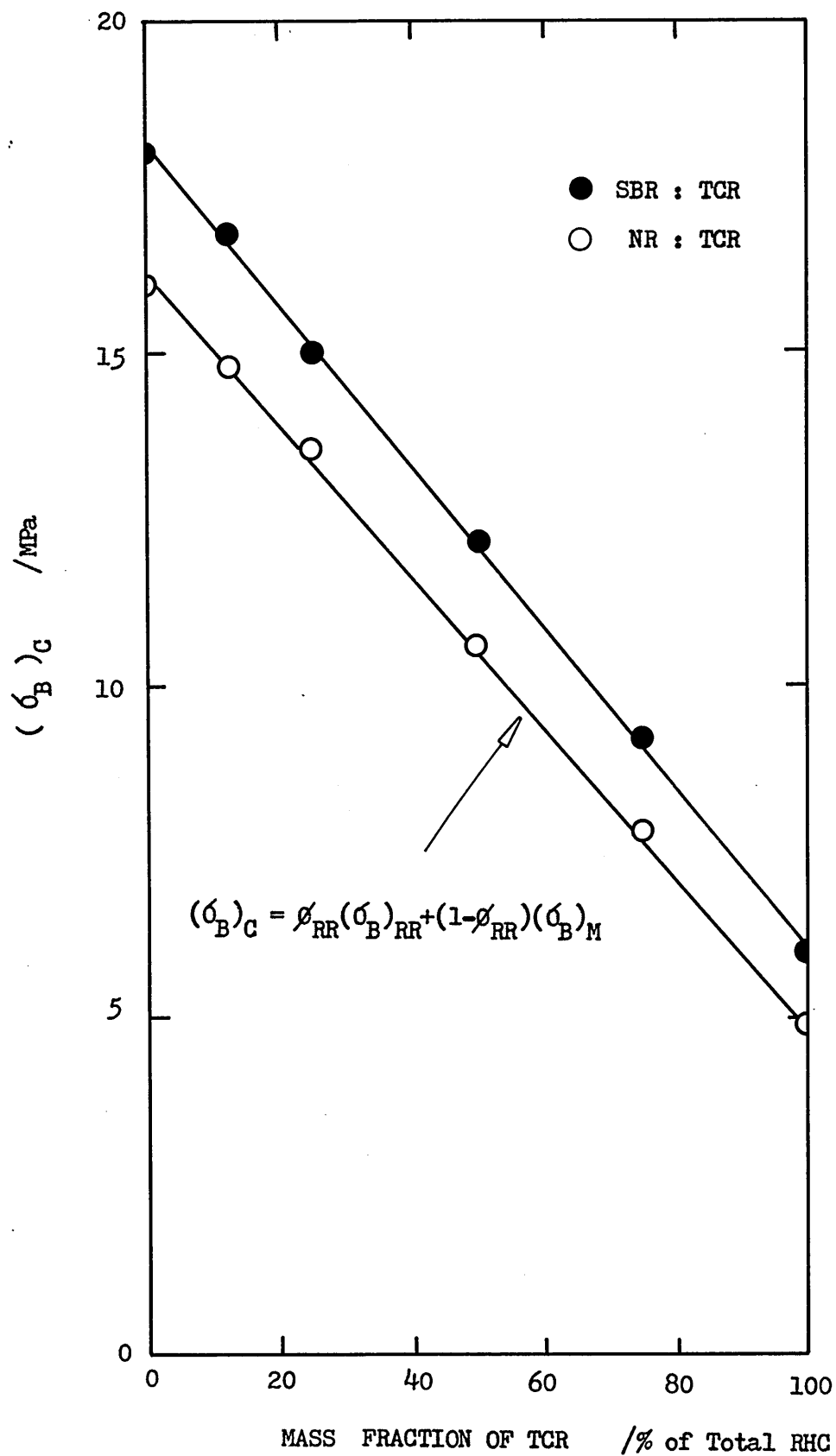


FIGURE 5.14 Variation of Tensile Strength as a function of the Amount of TCR Recycled Rubber expressed as a mass fraction of the Total RHC of the compound.
(Data from (28))

of these variables and types of tear behaviour makes it difficult to account for all facets of the problem. Studies of two of these variables have been reported for recycled rubber-rubber composites. These are the hardness of the particulate rubber filler and the amount of filler incorporated into a rubber compound.

(i) Effect of Hardness of Recycled Rubber Filler

Lambert and Boonstra (162) showed that for volume fractions of recycled rubber of less than some critical value, the incorporation of cryogenically ground vulcanized particulate SBR in an SBR rubber compound resulted in an increase in the tear strength of the composite. Some of their data is given in Figure 5.15. Enhanced tear strength was obtained with rubber particles derived from vulcanizate having hardness less and greater than the hardness of the base rubber compound. The tear strength of the compounds incorporating this form of recycled rubber increased in proportion to the hardness value over a wide range of hardnesses. It is difficult to account for this behaviour in terms of the difference in the physical properties of the two phases because of the complex relationship between elastic properties and hardness. This is discussed briefly in Appendix C.

(ii) Effect of Amount of Recycled Rubber Filler

The influence of the mass fraction of TCR recycled rubber (from Trellfax process) on the tear strength of composites has been studied in some detail (28). The variation of tear resistance as a function of the amount of TCR for two base rubber compounds is shown in Figure 5.16. These curves have been derived from data given in Reference 28. The compound formulations were adjusted to give approximately constant hardness (of 62 ± 2 IRHD) by increasing the amount of carbon black incorporated into the base compound in the range 50-0 phr for NR base, and 55-10 phr for SBR base. The cure system was not changed (the total RHC in all compounds also remained the same).

The important features of these results are that under the test conditions of this investigation:

- 1.) The tear strength of the base NR vulcanizate was larger than that of the base SBR vulcanizate. This behaviour has been widely reported in the literature (see for example Blow(72), p311).
- 2.) Although the tear strength of TCR-NR composites decreased steadily

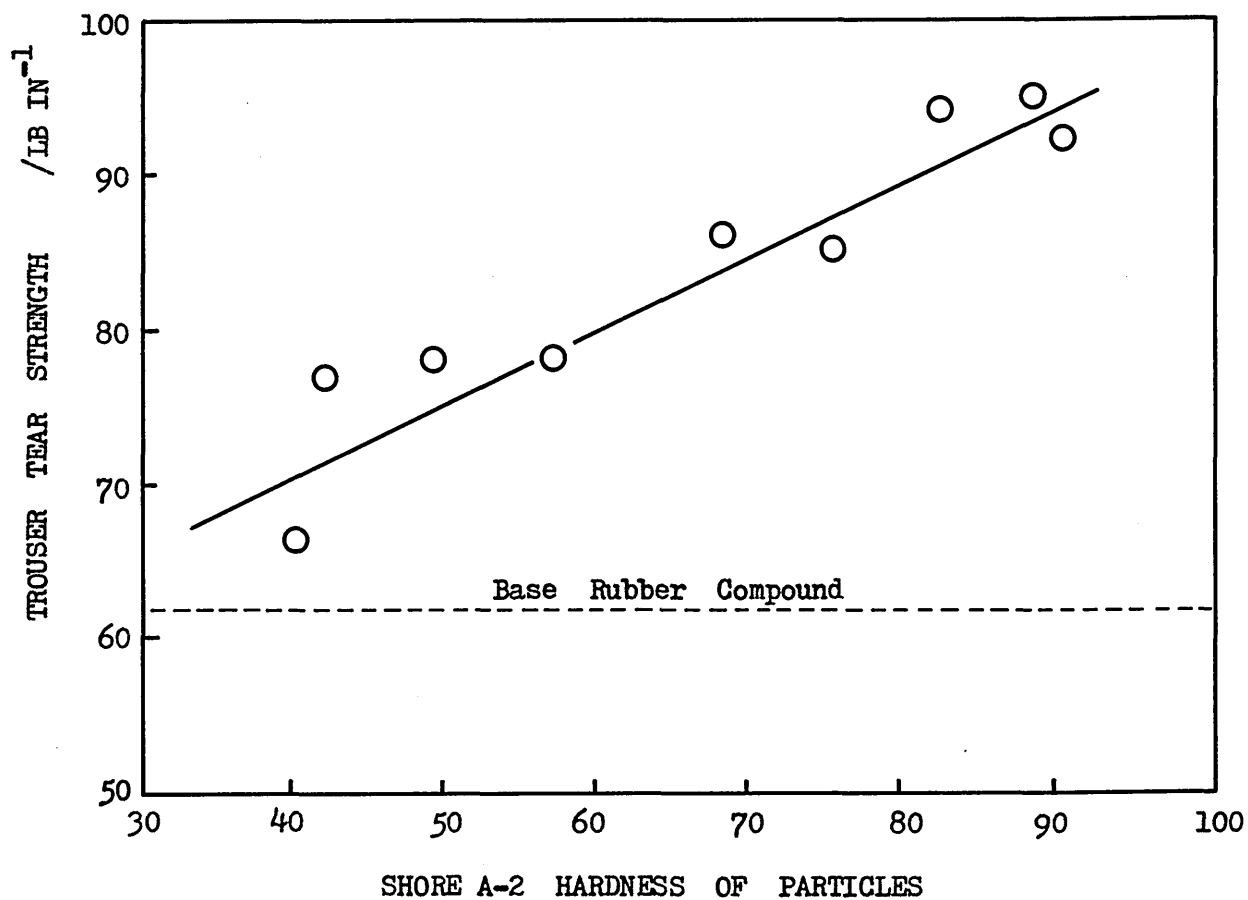


FIGURE 5.15 Variation of the Tear Strength of Compounds Incorporating 10% by volume of cryoground particles as a function of the Hardness of the Rubber from which the particles were derived. (from Lambert and Boontra (162))

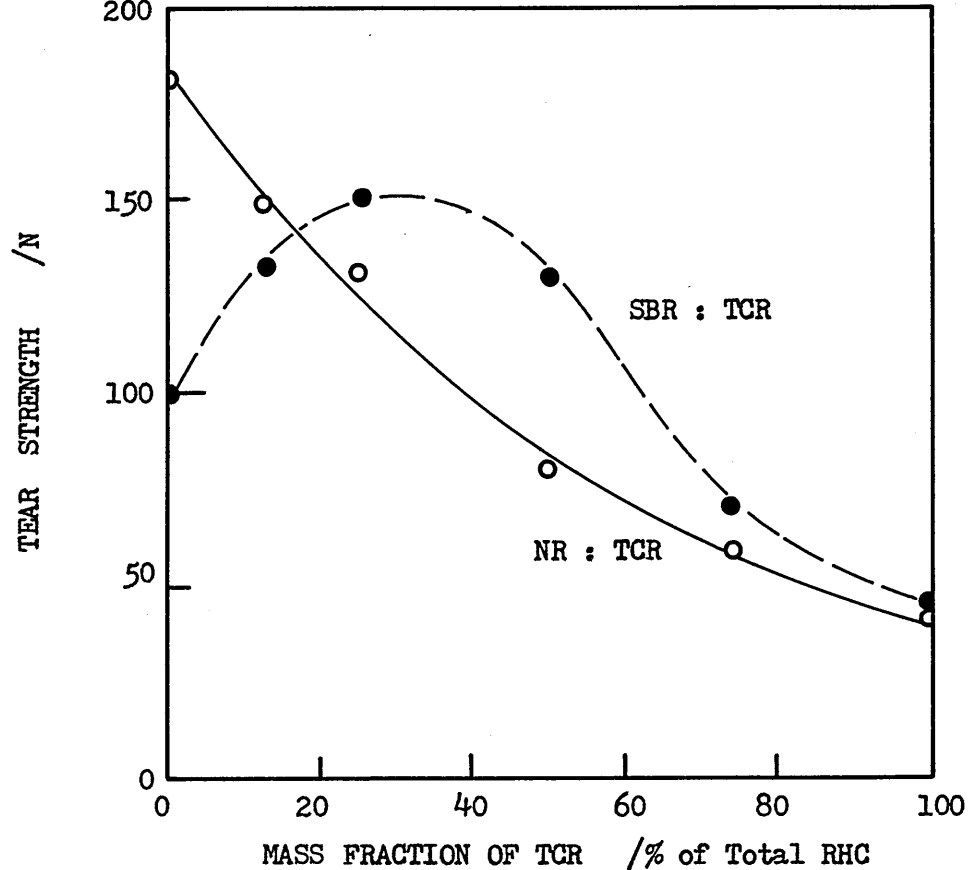


FIGURE 5.16 Variation of Tear Strength of NR:TCR and SBR:TCR Compounds as a function of Amount of TCR. (Data from (28))

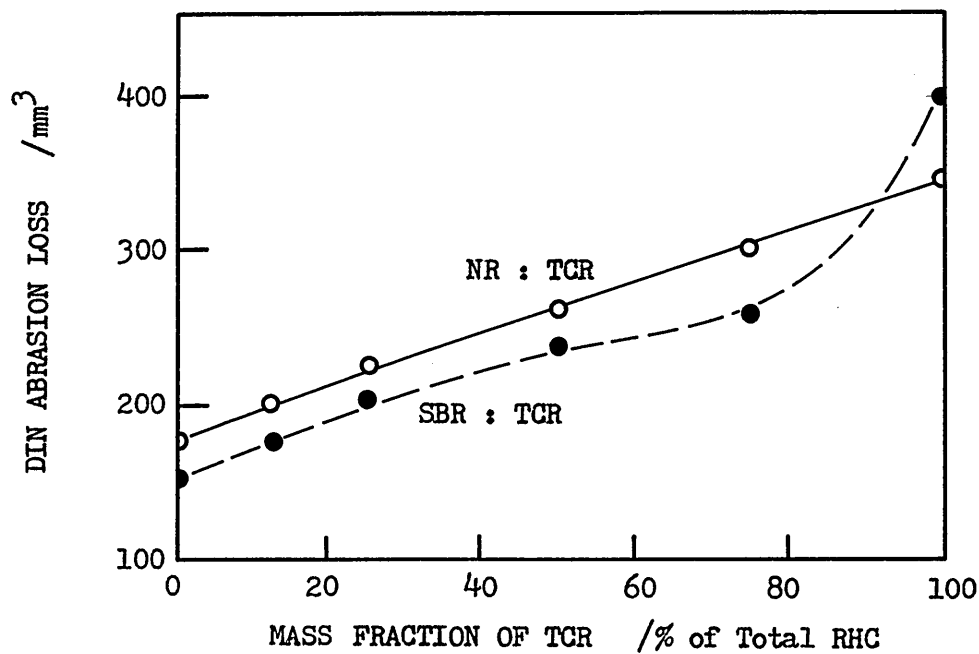


FIGURE 5.17 Variation of Abrasion Loss of NR:TCR and SBR:TCR Compounds as a function of Amount of TCR. (Data from (28))

with increasing ϕ_{RR} , the tear strength of TCR-SBR composites initially increased with increasing ϕ_{RR} and then passed through a maximum value. Similar behaviour for the SBR composites has been reported by Lambert and Boonstra (162), and Burgoyne et al (14). In the former case, the value of ϕ_{RR} for maximum tear strength was approximately the same as that for TCR-SBR composites shown in Figure 5.16 i.e. $\phi_{RR} \doteq 30\%$.

3.) At the maximum value, the tear strength for TCR-SBR composites was larger than that of the TCR-NR composites.

4.) At large values of ϕ_{RR} the tear strength of the two material systems was approximately the same.

There are two important areas which warrant some discussion: (1) the tear strength of SBR based rubber composite systems is enhanced and it passes through a maximum value; (2) the behaviour of NR based systems is different to that of SBR based systems. The discussion below attempts to provide an explanation.

As explained in Appendix C, many mechanisms have been postulated to account for tear strength enhancement by reinforcing fillers. One of these is tear tip deviation. This has been used to explain the high tear strength shown by multiphase elastomers such as strain crystallising materials (eg. NR) and triblock copolymers (eg. SBS), and solid particle (eg. glass beads) filled rubber composites (201). Under a particular range of temperature and tear rate, carbon black reinforced SBR compounds can also show this behaviour. Gent (133) has pointed out that abrasive wear might be considered as the detachment by tearing of small particles of material under the action of frictional forces. In this case, the conditions of tearing are such that large tear tip deviations are not possible. Abrasion loss data for the TCR material systems of Figure 5.16 are given in Figure 5.17.

It is seen that the abrasion loss of both TCR incorporated composite systems increased uniformly with increasing ϕ_{RR} . The ϕ_{RR} dependence of the two systems being much the same except at $\phi_{RR} > 75\%$. These results indicate that in both cases, the intrinsic tear strength (i.e. in the absence of tear tip deviation) decreased with increasing ϕ_{RR} . Hence, the tear strength enhancement observed with SBR based systems for unconstrained tearing might be due to the tear tip deviation mechanism. If this is the case, tear strength enhancement in SBR-recycled rubber compounds would not be effective under conditions where lateral

deviation of tear is prevented, such as by closely spaced reinforcing cords in vehicle tyres. This clearly has implications concerning the use of recycled rubber in this product application.

Lambert and Boonstra (162) explained the tear strength enhancement in SBR based compounds in terms of a localised tear deviation. They proposed that during tearing, stress relaxation occurs within the interfacial layer between the particulate rubber and the matrix, the stress transfer interface of equation 5.5. With bonded particles, the tear would propagate directly to the surface of the particle. The application of an increased stress is then required to continue the tear, either from the point of contact with the filler particle, or from a different region of high stress concentration.

The tearing behaviour of NR based compounds is more complex, partly due to the strain crystallising nature of NR. No satisfactory reason for TCR-NR composites not exhibiting these mechanism has yet been found.

Alternative mechanism can be put forward to explain the difference in the tear behaviour of NR and SBR compounds, based on the migration of curing agent from the matrix to the filler particles. Whelan and Lee (135) have shown schematically that the tear strength of rubbers passes through a maximum value with increasing crosslink density, v_e . In addition, Eirich and Smith (133) have shown that the tensile strength (σ_B) of rubber compounds passes through a maximum with increasing v_e , the value of v_e for maximum σ_B for NR (a strain crystallising rubber) being larger than that for SBR (an amorphous rubber). Combining these two observations, it is possible to construct hypothetical curves for the dependence of the inherent tear strength of NR and SBR matrix material on the crosslink density. These hypothetical curves are shown in Figure 5.18. Assuming that the compound formulations are adjusted to give the same value of crosslink density in the base rubber compounds, $(v_e)_R$, and that the migration of curing agent in the base rubber compound is related to the amount of incorporated recycled rubber, two situations can arise : (1) with NR, the tear strength will decrease monotonically with increasing ϕ_{RR} , and (2) for SBR, the tear strength will initially increase, passes through a maximum and then decrease; as reported for SBR compound incorporating TCR recycled rubber.

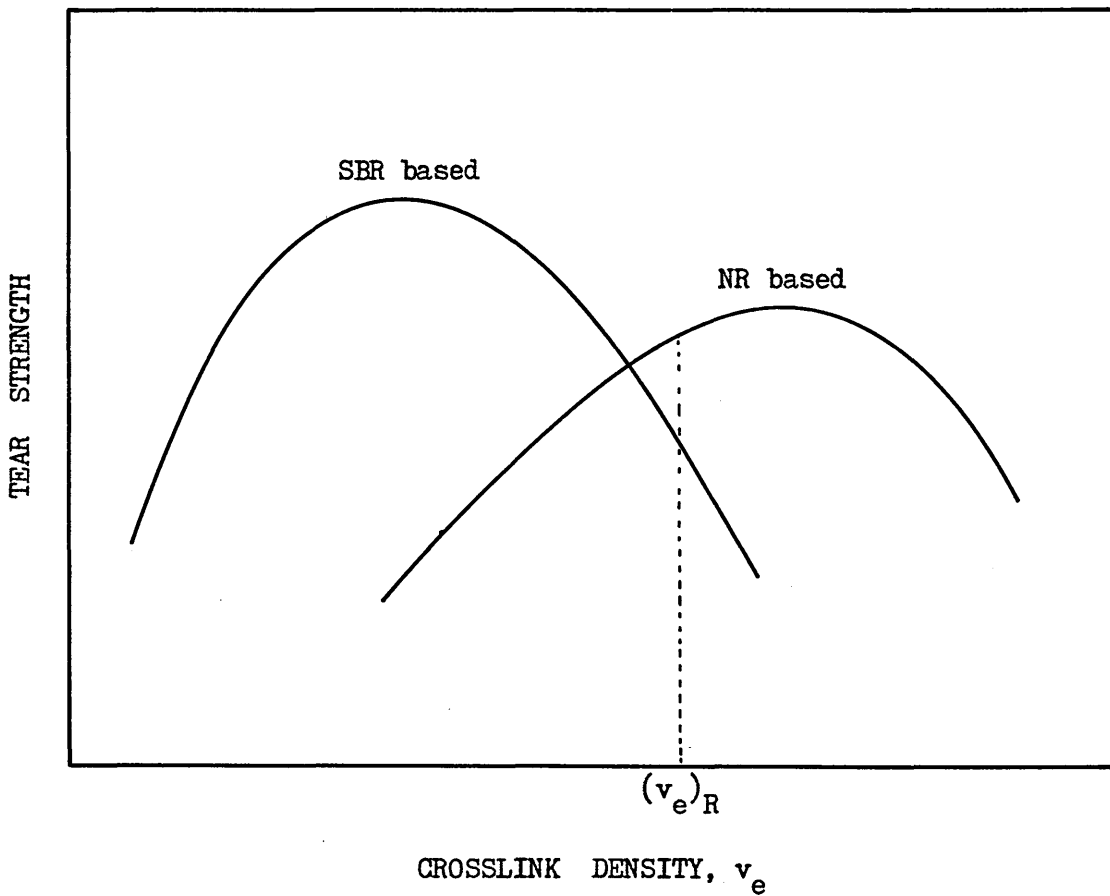


FIGURE 5.18 Hypothetical curves showing the variation of tear strength as a function of cross link density for NR and SBR compounds. For a compound with constant cure system the incorporation of particulate rubber filler will cause a decrease in crosslink density of the matrix rubber because of sulphur migration from matrix to crumb particles.

Our sulphur migration investigation described in Chapter Six provides further support to this hypothetical situation. It has confirmed that (1) the amount of curing agent migrated into the particulate rubber filler is greater with higher ϕ_{RR} ; (2) sulphur migration occurs more readily with SBR based composites than with NR based composites.

5.3 Experimental

The experimental work was divided into three parts; (i) the compounding and manufacture of rubber-rubber composite materials, (ii) the physical testing of these materials and (iii) the determination of structure and distribution of cure agent using electron microscopy and Energy Dispersive Analysis of X-ray, EDAX techniques. (i) and (ii) are described below, (iii) is discussed in detail in Chapter Six.

As explained in the publication which is incorporated into this thesis ("Influence of the cure system on the properties of vulcanizates incorporating particulate scrap rubber", PRI Annual National Conference on Crosslinking and network formation in polymers, London October 1982), compound formulations were chosen to provide a range of composite systems having widely different base rubber properties and possibly stress transfer interfaces. In addition, the use of crumb with powdered virgin rubber presents an attractive proposition with respect to the economics of material compounding (184).

(a) Compound Formulations and Material Manufacture

The particulate scrap rubber used in our investigation was 40 mesh, ambient ground, whole tyre crumb (WTC) supplied by Dunlop Ltd. This form of recycled rubber was used because particulate recycled rubber is the output of the potentially promising rubber recycling process (see Chapter Seven), and it is also a readily available commercial grade product widely used in the rubber industry.

The two base rubbers chosen to provide different matrix rubber properties were: SBR 1500 (a general purpose synthetic rubber), and a powdered natural rubber (Crusoe Standard supplied by Harrison and Crosfield Ltd).

A conventional accelerated sulphur vulcanizing system was used. It was based on MBTS (Dibenzthiazyl Disulphide) as primary accelerator, and ZDEC (Zinc Diethyl Dithiocarbamate) as secondary accelerator. The sulphur levels were changed arbitrarily, but the accelerators levels were increased in proportion to the total rubber hydrocarbon (RHC) contents in the compounds. The formulations for the compounds investigated are described in detail in Appendix E. They are summarised in Table 5.1.

The compounds were mixed in a laboratory two-roll mill at about 50°C.

Table 5.1 Summary of Compound Formulations and Vulcanization Conditions

Ingredient	WTC - SBR (phr)	WTC - NR (phr)
Base Rubber	100	100
WTC crumb	0 - 50	0 - 50
Zinc Oxide	5	5
Stearic Acid	2	2
Antioxidant	1	1
Sulphur	1.0 - 10	2.5 - 10
MBTS	1.5 - 1.88	1.0 - 1.25
ZDEC	0.2 - 0.25	0.1 - 0.13
Vulcanization		
Time /min	30 - 15	15
Temperature /°C	150	140
Pressure /tpi	1.0	1.0

Master-batching technique had been used to ensure consistency in compounds of slightly different formulation. The mixes were allowed to stand at room temperature for at least 24 hours before being moulded in a hydraulic press with a pressure of one ton per square inch and at appropriate vulcanization conditions. The mixing technique and moulding procedure, together with detailed vulcanization conditions are described in Appendix E. The vulcanization conditions are also summarised in Table 5.1. The moulded sheets with a thickness of about 2 mm were allowed to stand at room temperature for at least 24 hours before being tested.

(b) Test Procedure

Samples of the composite systems were prepared from the moulded sheets using a standard dumb-bell cutter. The physical property testing were carried out on an Instron tensile tester at strain rate of 1.1 s^{-1} (cross-head speed of 5 cm s^{-1} and initial sample length of 4.5 cm), at room temperature. The thickness of each individual test sample was obtained by averaging several micrometer thickness measurements along the length of the sample prior to testing. Six samples from each composite system were tested, from which average physical properties were calculated.

Precautions have been taken to ensure that the initial sample length between the grips (sample holders) was kept at a constant 4.5 cm. One major problem with testing the high strength NR based samples has been the slippage of the sample from the grips. This was partially overcome by sandwiching the sample at the grips with sand-paper, hence improving the grip.

(a) Introduction

Many theoretical models have been proposed for property relationships in composite materials (see Appendix D for examples). The most widely used model is based on the linear law of mixtures which has been used for continuous fibre reinforced composites (eg. 151,152). One particular form of this model has been used by McNally et al (161) for short fibre filled thermoplastics composites, and when expressed in terms of parameters appropriate to a recycled rubber-rubber composite system gives

$$(E_0)_C = (E_0)_m(1-V_{RR}) + R(E_0)_{RR}V_{RR} \quad (5.6)$$

$$(\sigma_B)_C = (\sigma_B)_m(1-V_{RR}) + R'(\sigma_B)_{RR}V_{RR} \quad (5.7)$$

where E_0 is the initial elastic modulus, σ_B is the tensile strength and V_{RR} the volume fraction of recycled rubber, and the subscripts have their usual meaning. The reinforcement factors, R and R' are related to the adhesive bond strength at the crumb-matrix interface, and can take a value between zero and unity.

Although this simple law of mixtures model has limited use for the analysis of particulate filled composites, it should provide a suitable basis for analysis in current work. Some justification in the use of this model for our WTC-rubber composites was given in Section 5.2 (b) where it was shown that the tensile strength of TCR incorporated vulcanizates closely followed equation 5.7 with $(\sigma_B)_m > (\sigma_B)_{RR}$ and $R' \approx 1.0$.

The difficulty in testing WTC-NR composites has led to an incomplete set of data for the WTC-NR series. Emphasis has been given to the WTC-SBR series of composite materials in the discussion below.

(b) Elastic Properties

The initial elastic moduli, $(E_0)_C$, of the WTC-SBR composites are presented in Figure 5.19, and that for WTC-NR are presented in Figure 5.20. It is seen that for WTC-SBR systems, the initial modulus increases with increasing WTC content, while for WTC-NR composites, $(E_0)_C$

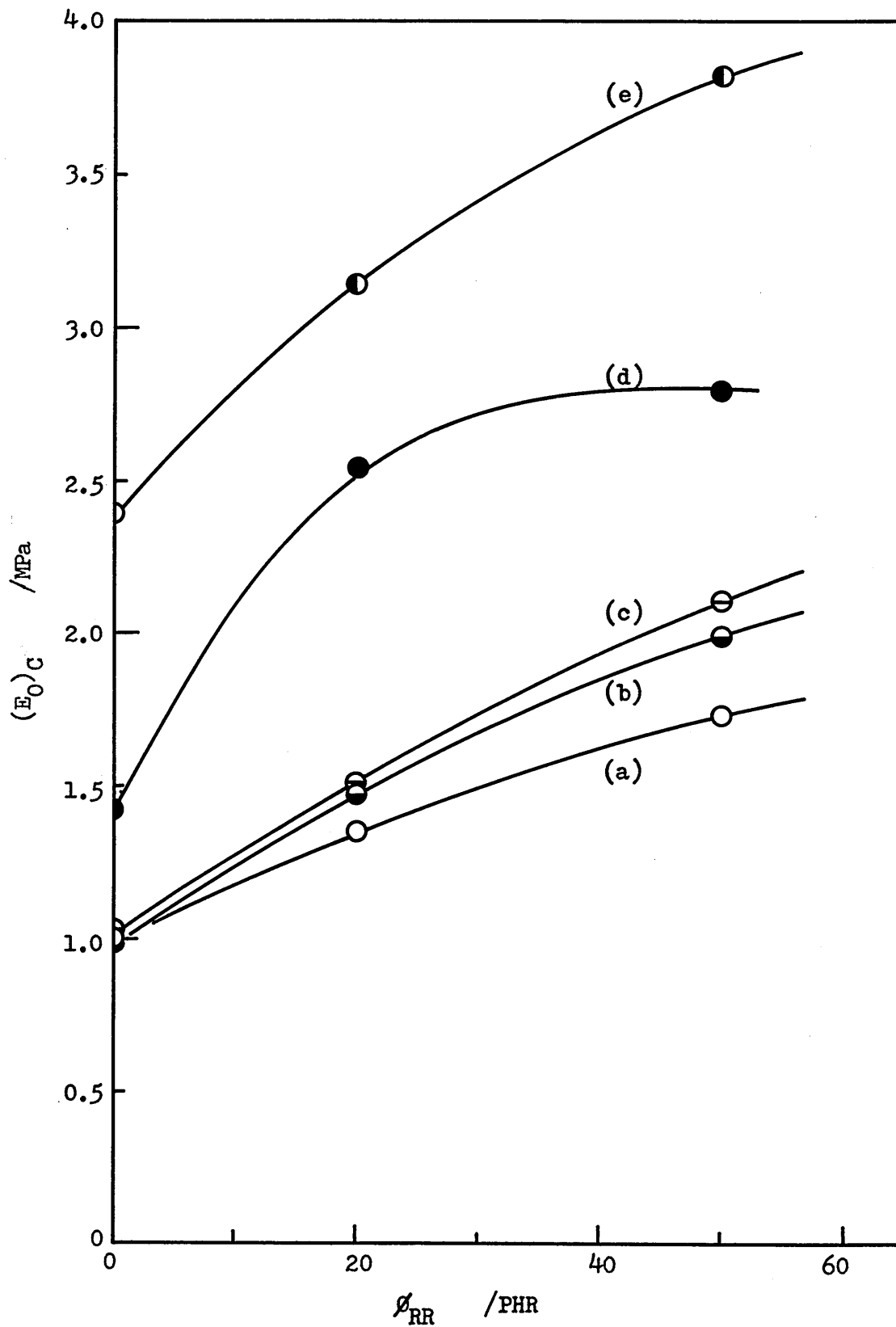


FIGURE 5.19 Variation of initial modulus as a function of WTC recycled rubber loading, ϕ_{RR} , expressed in PHR, for WTC-SBR 1500 systems. (a) S=1.0; (b) S=1.5; (c) S=2.0; (d) S=5.0 and (e) S=10.0 phr.

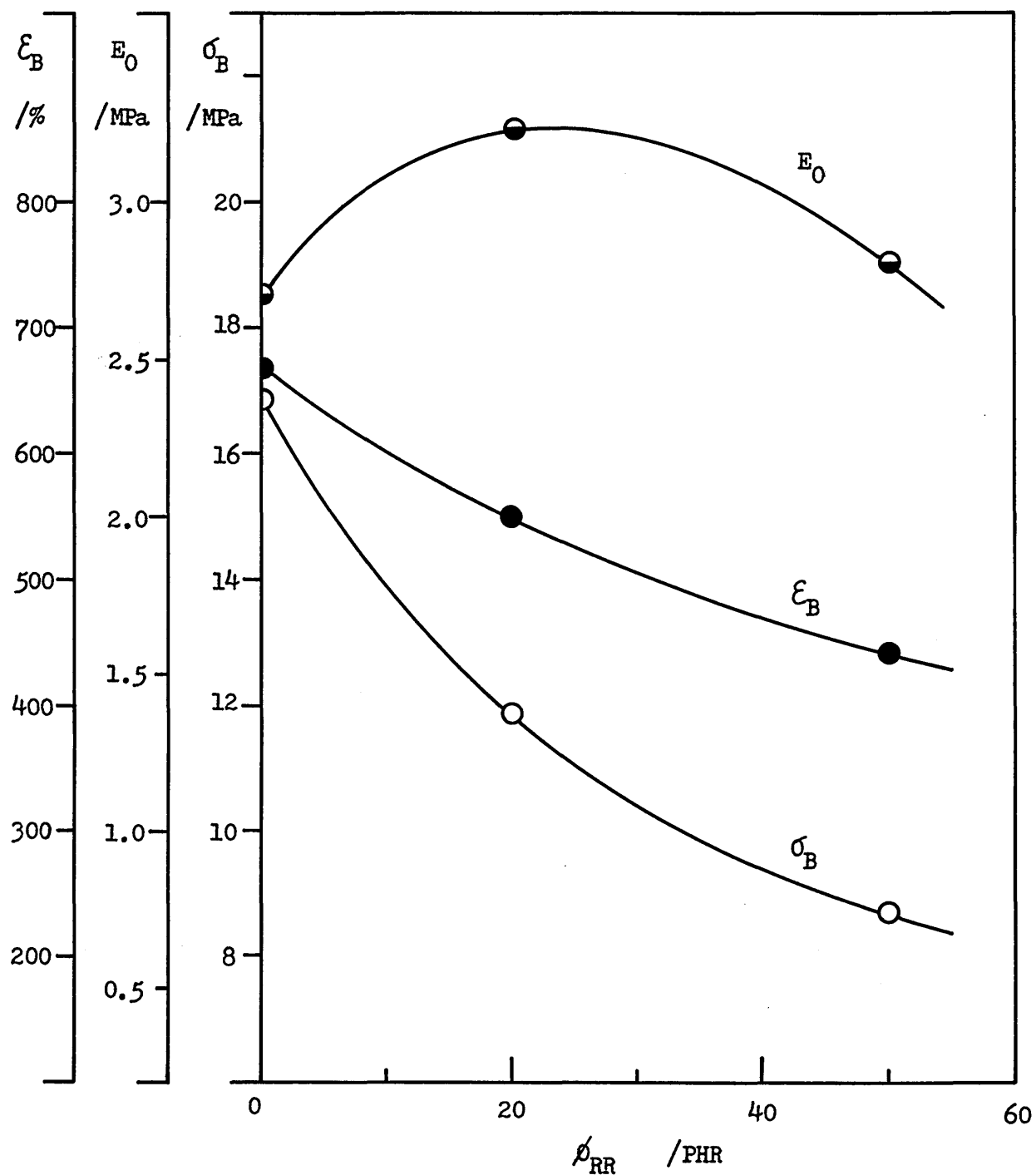


FIGURE 5.20 Physical properties of WTC-NR composite systems as a function of the amount of WTC recycled rubber incorporated into the compounds, $S = 2.5$ phr.

passes through a maximum. This is in contradiction with the general observation made in Section 5.2 (a), which may imply that for WTC-SBR composites, the initial modulus of the WTC, $(E_0)_{RR}$, is greater than $(E_0)_m$, the initial modulus of the matrix. The behaviour of WTC-NR is in agreement with some observations, for example the fluorocarbon rubber composite. It can also be seen that for WTC-SBR, $(E_0)_C$ increases with increasing level of sulphur content.

By presenting the initial modulus data of the WTC-SBR systems, in the form of modulus ratio $(E_0)_C / (E_0)_m$ as a function of the mass fraction of WTC, as shown in Figure 5.21, and from the predictions of Kerner model for two phase composite materials (see Appendix D, Figure D.4), it can be inferred that α is greater than unity for these WTC-SBR materials. (α is defined as $(E_0)_{RR} / (E_0)_m$). Hence, indicating that $(E_0)_{RR} > (E_0)_m$ as intuitively inferred above. This, in fact is the case, as the base SBR compounds have very low modulus values (see Appendix E) compared with that of a typical tyre rubber compound (of about 4 MPa (71)). The shapes of the curves in Figure 5.21 are in fair agreement with the Kerner model (except for composite with $S = 5.0$ phr). With increasing sulphur content, the $(E_0)_m$ is expected to increase (due to a higher crosslink density, see Figure C.6), and hence, α to decrease. However, this agreement does not seem to apply to all sulphur levels, especially at low levels of sulphur. This peculiar behaviour may indicate that at low sulphur levels, sulphur migration from the matrix into WTC particles may have occurred, or that the Kerner model does not apply to this material systems. (The migration of sulphur will increase $(E_0)_{RR}$ and hence increases α).

The initial elastic modulus of the WTC-SBR composites can be examined using the linear law of mixtures model described by equation 5.6. The $(E_0)_C$ values of the composites are plotted as a function of the volume fraction of the incorporated WTC in Figure 5.22. The broken lines are the relationships predicted by equation 5.6. It can be seen that although the general trend of the property values is in the correct direction, discrepancies from the predicted trends vary substantially. The prediction for $S = 10.0$ phr system underestimates the actual values, while it overestimates the actual values for $S = 1.0$ phr system. These discrepancies from the model could have due to many reasons, one of the most important of which is the influence of the

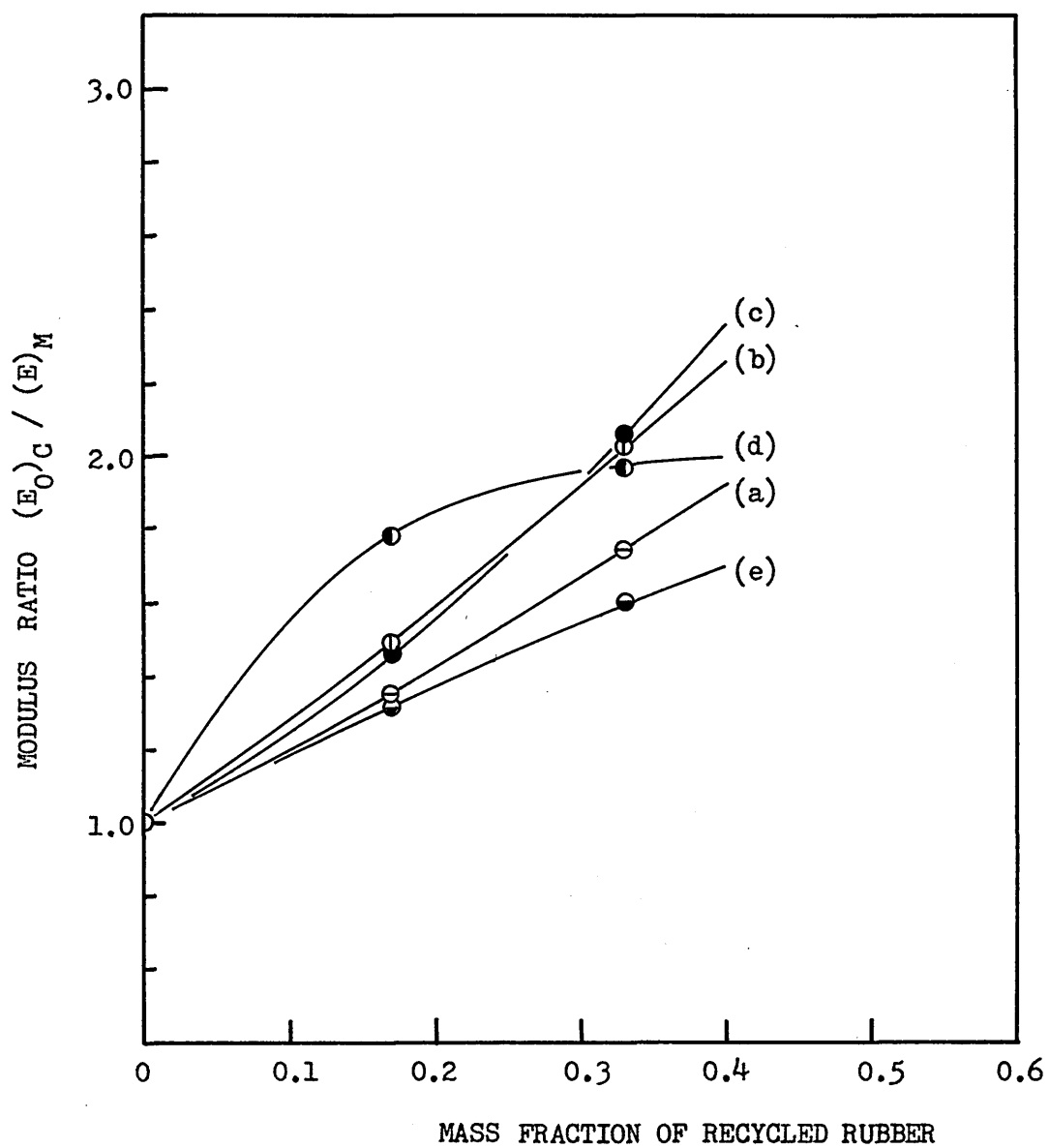


FIGURE 5.21 Variation of initial elastic modulus as a function of the amount of WTC recycled rubber incorporated into the compounds for WTC-SBR 1500 composites. (a) S=1.0; (b) S=1.5; (c) S=2.0; (d) S=5.0; and (e) S=10.0 phr.

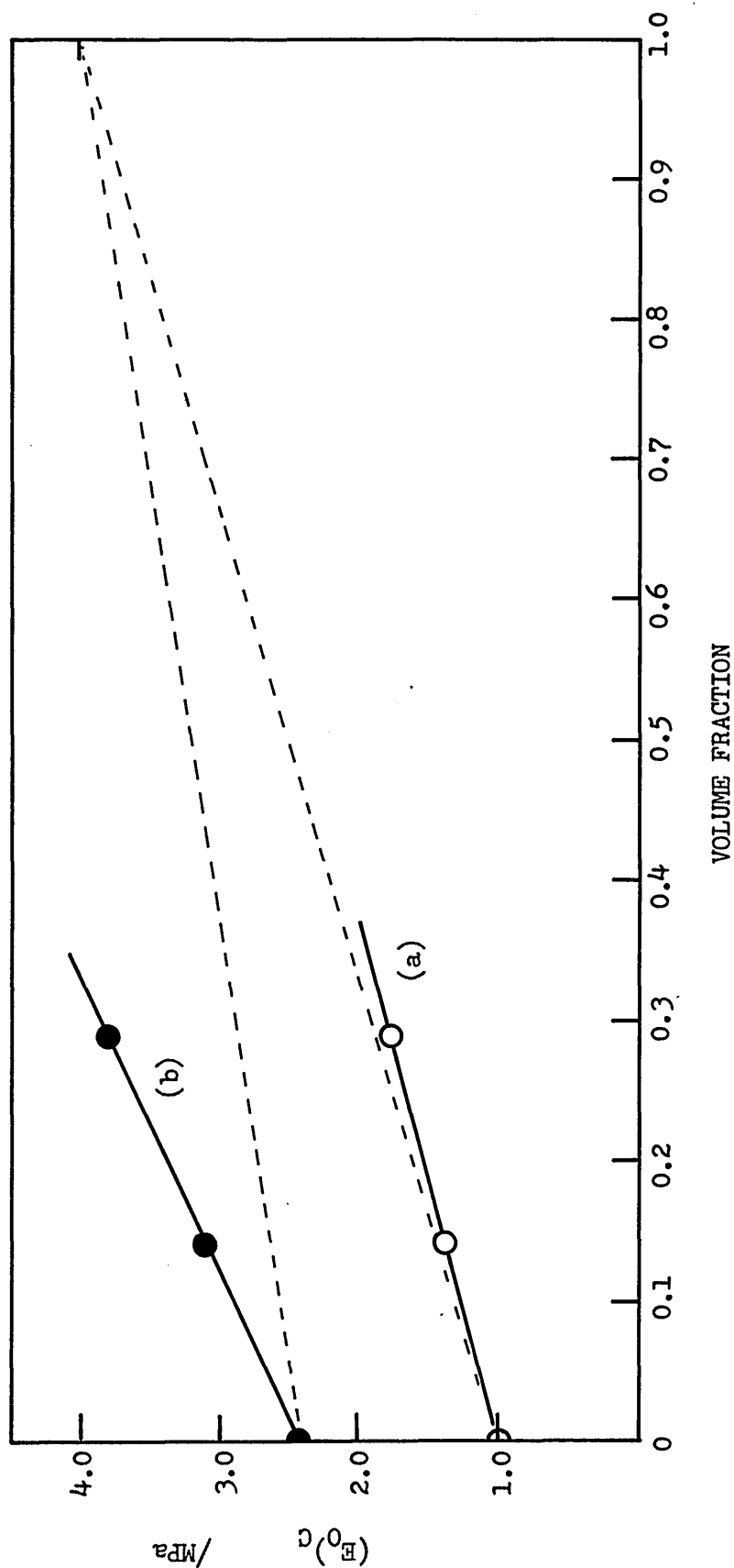


FIGURE 5.22 Variation of the Initial Elastic Modulus as a function of the Volume Fraction of whole tyre crumb. (a) WTC - SBR 1500, S=1.0 phr ; (b) WTC - SBR 1500, S=10.0 phr.

vulcanization process through curative migration.

The effect of increasing the sulphur curing agent in the vulcanization system on the initial modulus of the WTC-SBR composites are presented in Figure 5.23. It is seen that, as expected (see discussion in Section 5.2 (a)), the $(E_0)_C$ increases with increasing sulphur loading in the matrix mix which is in agreement with the inference from the work of Grebenkina and coworkers (160).

(c) Strength Properties

As discussed in Section 5.2 (b), the curing agent content of the base rubber can influence the strength properties of recycled rubber incorporated composites. The results of our investigation with WTC-SBR composites are presented in Figures 5.24 and 5.25. In general, apart from the initial peculiar behaviour for $\phi_{RR} = 0$ phr and $\phi_{RR} = 20$ phr systems at low sulphur levels, the composites followed the typical trends i.e. increasing tensile strength, $(\sigma_B)_C$, and decreasing elongation-at-break, ϵ_B , with increasing sulphur loading. It is interesting to note that the filled composites, in fact, have a higher $(\sigma_B)_C$ than the unfilled matrix compounds. This could be due to the very low strength of the matrix compounds and the relatively high tensile strength of the recycled rubber crumb. The increase in $(\sigma_B)_C$ with increasing sulphur level is more profound with composites with higher WTC loadings, indicating that there may be an improvement in the interfacial bonding between the particles and the matrix with increasing curative level. The redistribution of sulphur in the WTC-SBR systems is studied in more detailed in Chapter Six.

The effect of the amount of WTC on the tensile strength and elongation-at-break are presented in Figure 5.26 and 5.27 respectively. It can be seen that the $(\sigma_B)_C$ increases monotonically with increasing WTC incorporation. As pointed out above, this strength property enhancement may be due to the low strength value of the matrix and indicating a partially bonded system. The ϵ_B data of the WTC-SBR composites show that the incorporation of WTC decreases ϵ_B , and that ϵ_B passes through a minimum value with increasing ϕ_{RR} .

Figure 5.28 shows the relationships of $(\sigma_B)_C$ and ϕ_{RR} when ϕ_{RR} is expressed as a percentage of the WTC rubber hydrocarbon (RHC) over the total RHC content in the composite. The lines for S=1.5, 2.0 and 5.0 phr

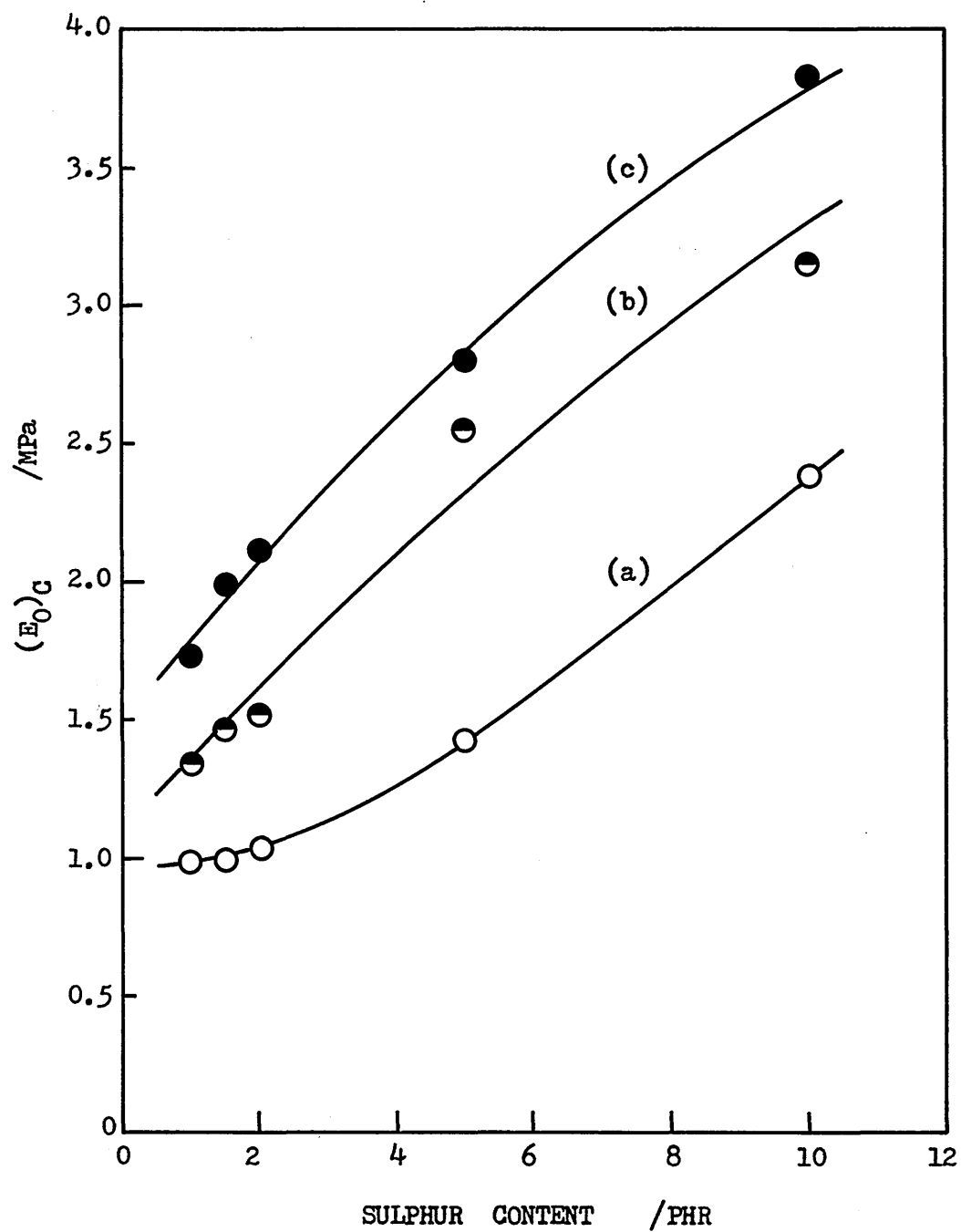


FIGURE 5.23 Effect of cure system on $(E_0)_C$ of WTC-SBR 1500 systems.
 (a) $\phi_{RR} = 0$ phr; (b) $\phi_{RR} = 20$ phr; and (c) $\phi_{RR} = 50$ phr.

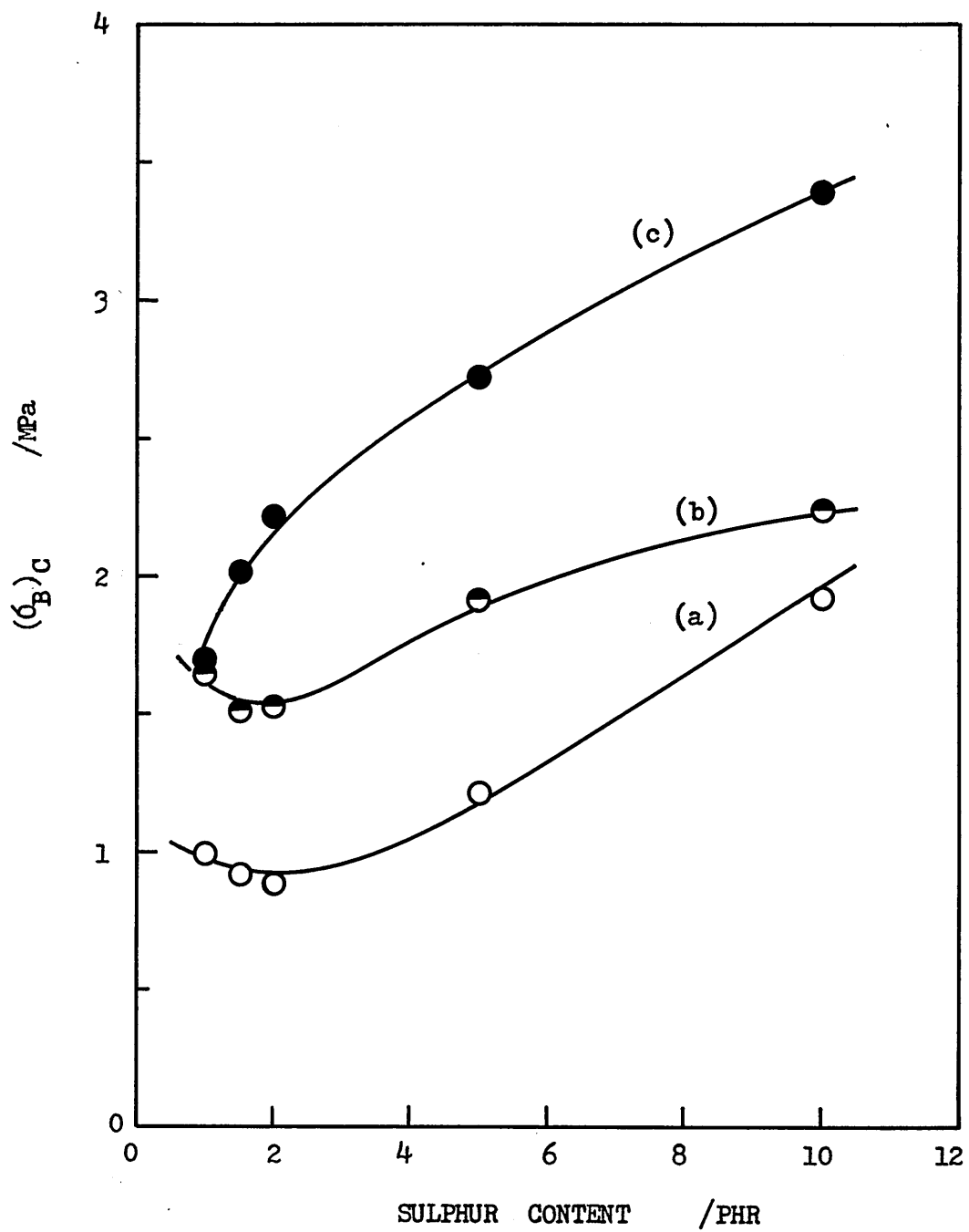


FIGURE 5.24 Effect of cure system on $(\sigma_B)_C$ for WTC-SBR 1500 composites.
 (a) $\phi_{RR} = 0$ phr; (b) $\phi_{RR} = 20$ phr and (c) $\phi_{RR} = 50$ phr.

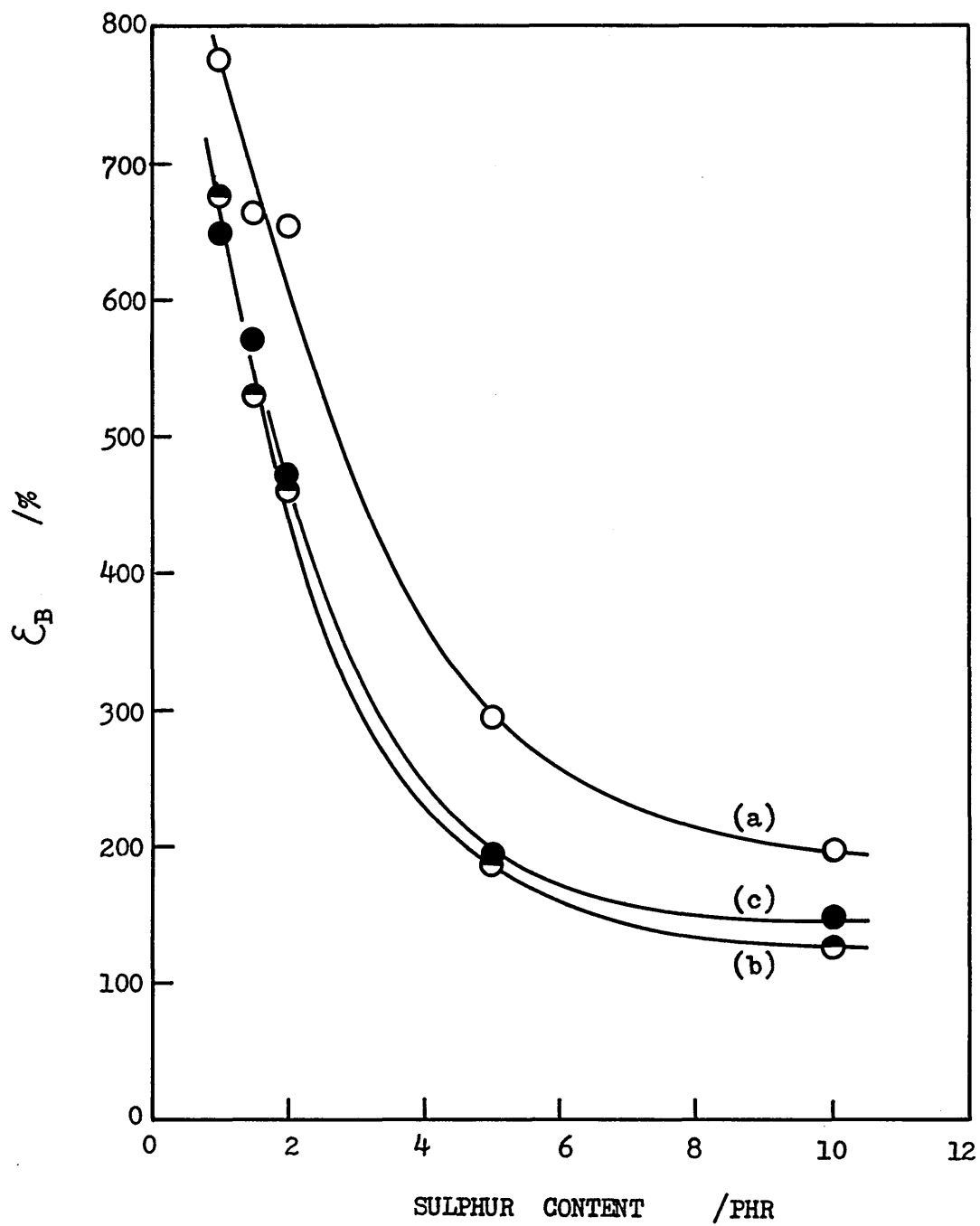


FIGURE 5.25 Effect of cure system on ϵ_B for WTC-SBR 1500 compounds.
 (a) $\phi_{RR} = 0$ phr; (b) $\phi_{RR} = 20$ phr; and (c) $\phi_{RR} = 50$ phr.

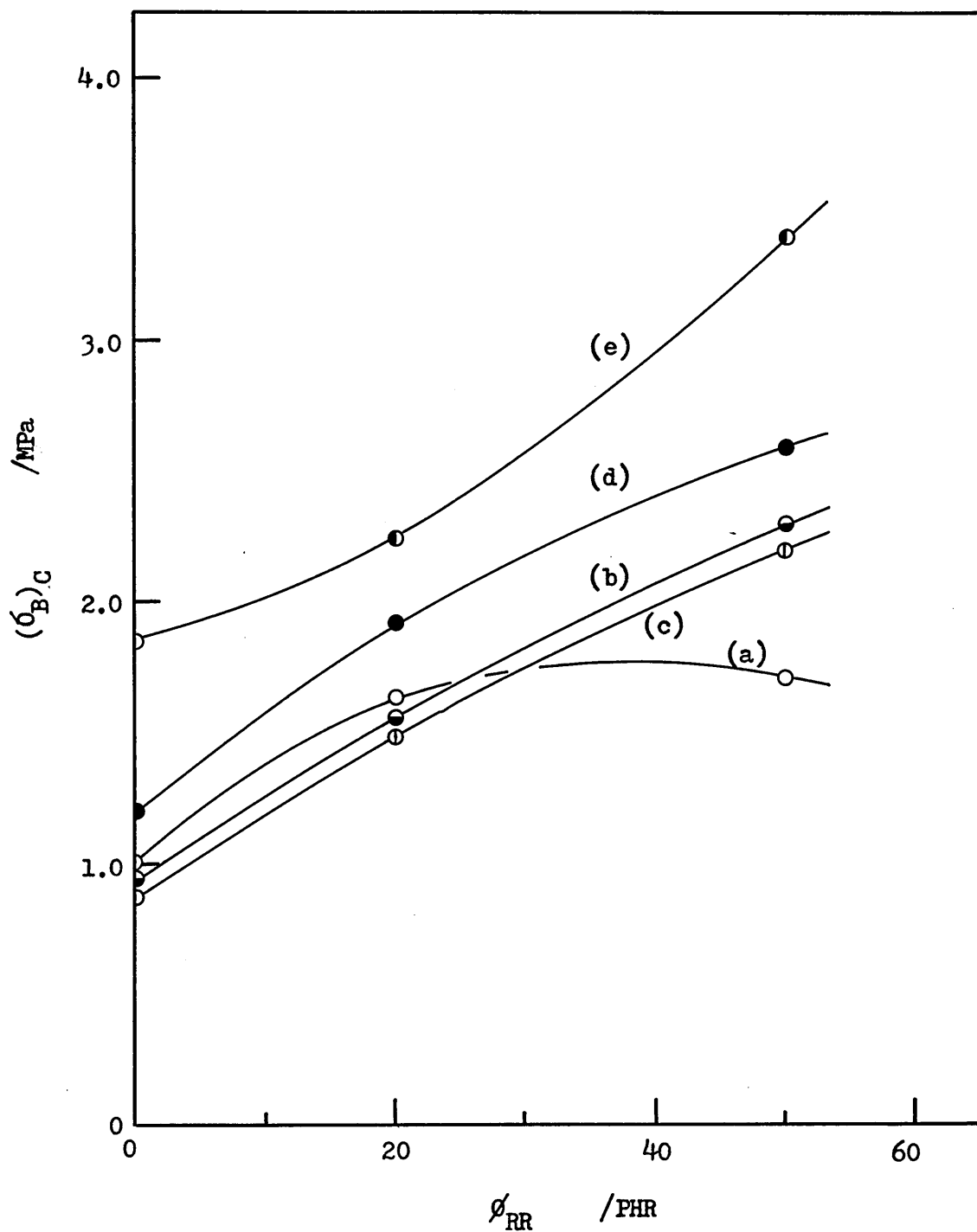


FIGURE 5.26 Effect of ϕ_{RR} on $(\sigma_B)_C$ at constant sulphur loadings for WTC - SBR 1500 composites. (a) $S = 1.0$; (b) $S = 1.5$; (c) $S = 2.0$; (d) $S = 5.0$ and (e) $S = 10.0$ phr.

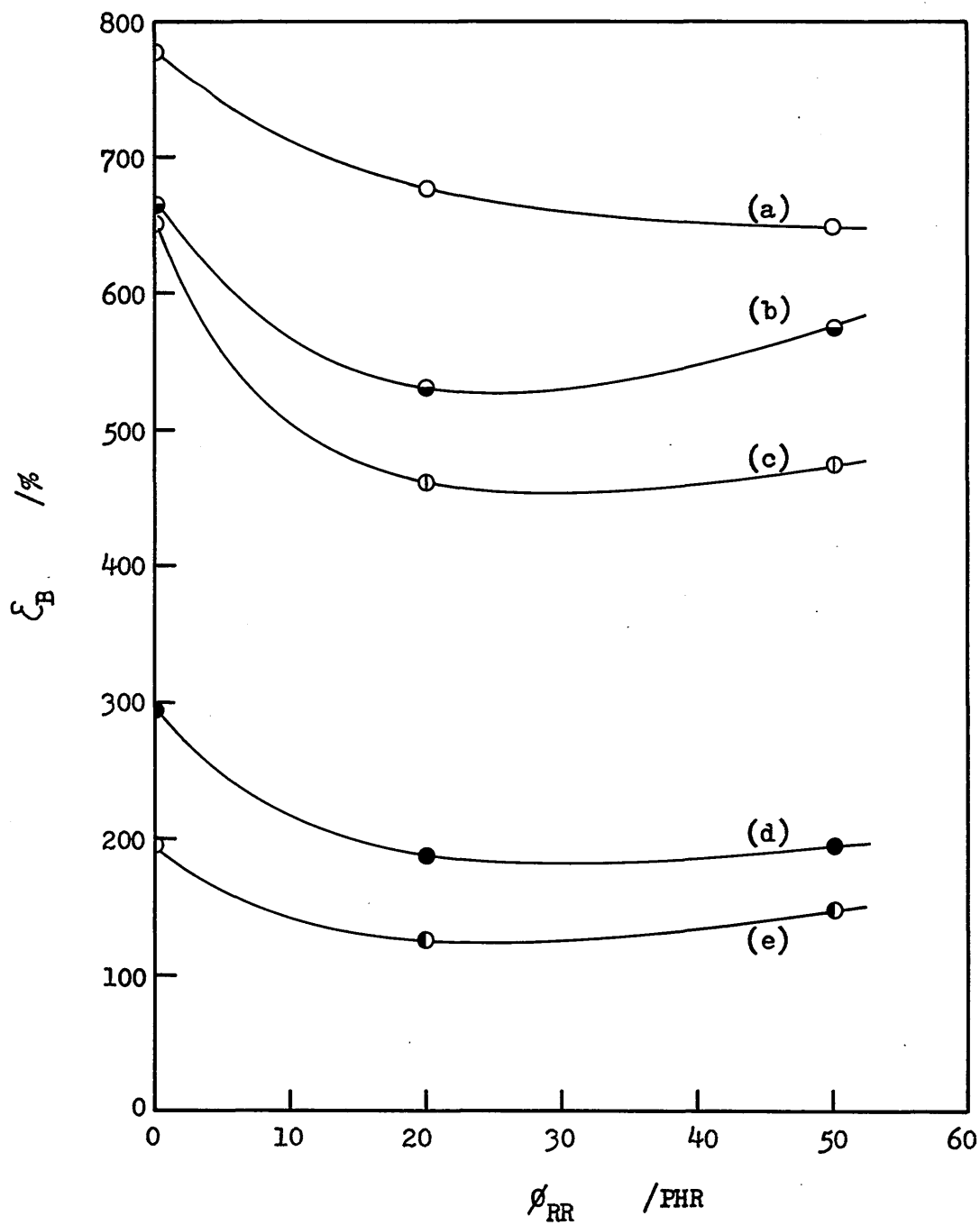


FIGURE 5.27 Effect of ϕ_{RR} on ξ_B at constant sulphur loadings for WTC-SBR 1500 compounds. (a) S=1.0; (b) S=1.5; (c) S=2.0; (d) S=5.0; and (e) S=10.0 phr.

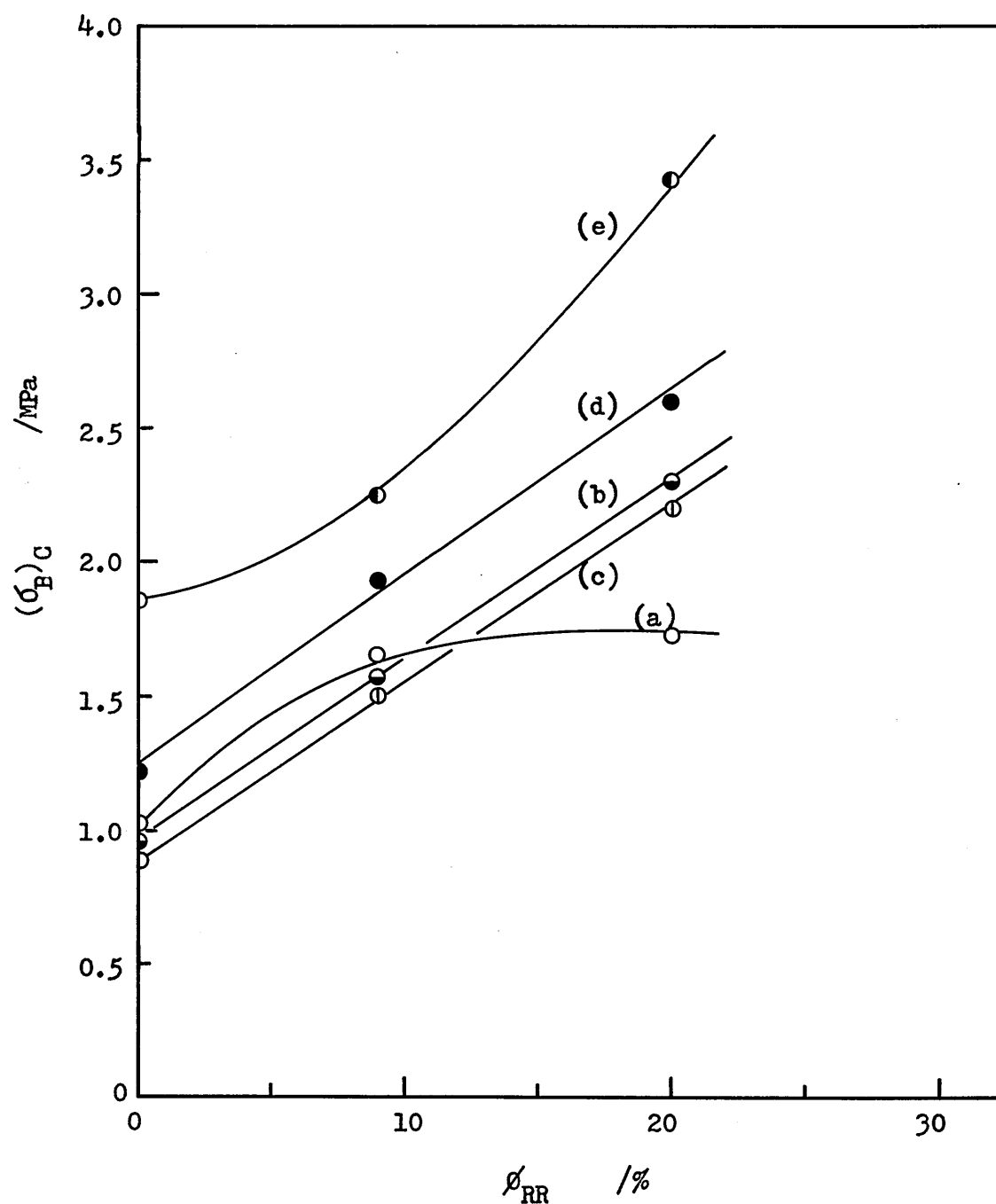


FIGURE 5.28 Effect of ϕ_{RR} on $(\sigma_B)_C$ at constant sulphur loadings for WTC-SBR 1500 systems. ϕ_{RR} is expressed as mass fraction of WTC RHC over the total RHC in the system. (a) $S=1.0$; (b) $S=1.5$; (c) $S=2.0$; (d) $S=5.0$ and (e) $S=10.0$ phr.

show a linear relationship with ϕ_{RR} . This indicates that, at these curative loadings, the WTC-SBR composites may be represented by the linear law of mixtures model, equation 5.7. In this case, the reinforcement parameter, R' appears to lie between its limits, indicating that it is an imperfect bonding system (the lines will not pass through the estimated $(\sigma_B)_{RR}$ value of about 20 MPa at $\phi_{RR} = 100\%$).

At very low and very high sulphur curing agent levels, curvilinear relationships still prevailed, as shown in Figure 5.28. This indicates that the failure mechanism for WTC-SBR at these sulphur levels may be quite different from that of the rest of the composite series.

(d) Stress-Strain Behaviour and the Mechanics of Rubber-Rubber Composites

Traditional methods of evaluating the physical properties of recycled rubber-rubber composite materials do not allow the identification of the processes which govern the important physical properties such as stiffness, tensile and tear strength. In order to obtain a true understanding of the mechanics of these materials, it is necessary to account for their stress-strain behaviour. None of the workers, whose material systems are discussed above, have attempted any such studies, and a detailed literature search has shown that this has not been reported elsewhere. The following discussion is based on the material property data obtained in our experimental investigations. Full details of these results are given in Appendix E.

The stress-strain plots for the two material systems i.e. WTC-NR and WTC-SBR are shown in Figure E.1 through E.9 (in Appendix E). In general, the stress-strain relationships for the material systems are similar as those for normal rubber vulcanizates. Both exhibiting Gaussian and non-Gaussian behaviours, debonding between matrix and particulate filler and strain induced crystallization (201,202,203). Given the large number of variables involved, it is only possible to discuss in detail the mechanisms responsible for the behaviour by considering specific systems. As a starting point, it is useful to examine the basic stress-extension ratio diagrams. The stress-extension ratio diagrams for two material systems, WTC-NR and WTC-SBR ($S=1.0$ phr) are reproduced in Figure 5.29, where the ratio of $\sigma_C / (E_0)_C$ is plotted as a function of extension ratio, λ . Reduced or normalised stresses are used so to emphasise the influence of incorporating recycled rubber crumb on the shape of the stress-strain relationship.

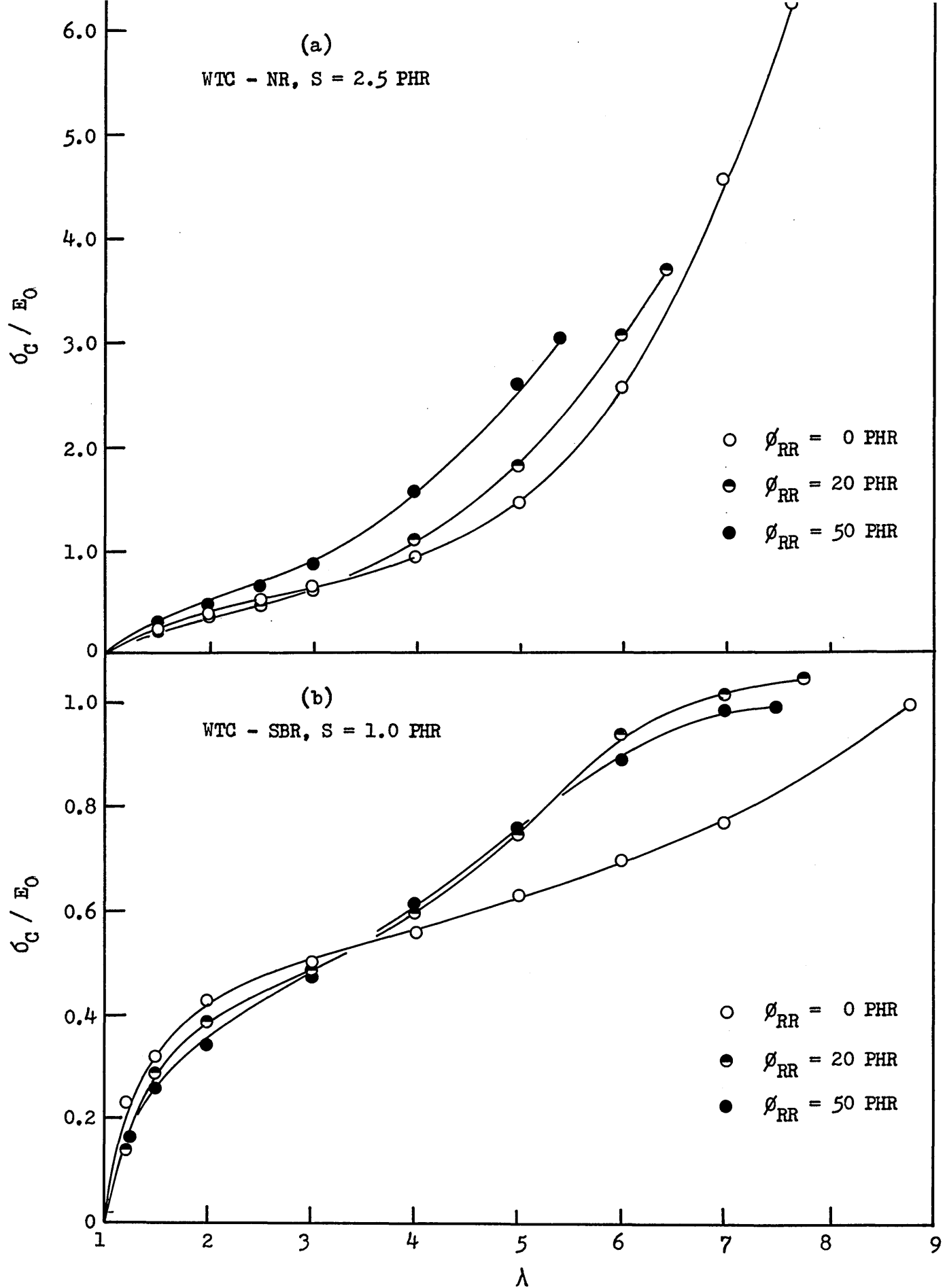


FIGURE 5.29 Representative stress-strain diagrams of WTC-NR and WTC-SBR composites.

It is seen that for the NR based system, in which the strength of the matrix material was expected to be similar to those of the crumb(71), the stress-strain relationships are much the same as those for conventional elastomers. The tensile strength, $(\sigma_B)_C$, and elongation-at-break, ϵ_B , decreased with increasing crumb content. However, for the WTC-SBR systems, in which the strength of the matrix rubber was less than that of the crumb, the relationships were more complex. At low λ , the $(\sigma_B)_C / (E_0)_C$ ratio for the crumb filled materials was less than that for the unfilled rubber. The property curves for this particular WTC-SBR system intersected at the same λ value of about 3.4. At high λ values, the $(\sigma_B)_C / (E_0)_C$ ratios for the composites exceeded those of the unfilled rubber. It is seen that for the WTC filled SBR systems, the property curves at large extensions tended to become concave to the λ -axis. This behaviour has been observed previously for rigid particles filled rubber compounds and was attributed to debonding between matrix and filler (201). The point of intersection between the curves for the WTC-SBR systems shifted to lower values of λ as the sulphur curing agent content was increased from 1.0 to 10.0 phr (see Figure E.7 through E.9 in Appendix E). At large sulphur content, 5 and 10 phr in this case, the $(\sigma_B)_C / (E_0)_C$ curves at low λ (< 2) for different crumb loadings, ϕ_{RR} , were coincident. The reasons for this behaviour are not known, but it is thought to be related to variations in the value of the ratio of the Mooney constants, C_2 / C_1 .

The conventional technique of analysing the stress-strain behaviour of elastomers is to use two mathematical models, one to describe the Gaussian behaviour at low extensions, and one for the non-Gaussian characteristics at high strains. The Mooney-Rivlin equation (49), which is the most widely accepted low-extension model, can be written in the form

$$\frac{\sigma}{2(\lambda - \lambda^{-2})} = C_1 + \frac{C_2}{\lambda} \quad (5.8)$$

where C_1 and C_2 are constants characteristic of the rubber network. A non-Gaussian model based on the inverse Langevin function can be used for the high extensions. A simplified form of this non-Gaussian model has been proposed by Kaelble (147), and used by Hodgkinson (132), can be written in the form

$$\frac{1 - 1/\lambda}{\sigma} = \frac{1}{E_L} - \frac{\lambda^2}{E_L \lambda_L^2} \quad (5.9)$$

where E_L and λ_L are the terminal elastic modulus (at break) and the terminal extension ratio respectively.

The Mooney-Rivlin and non-Gaussian plots for the materials are given in Figures E.10 to E.20 in Appendix E. Representatives of the behaviour observed are given in Figures 5.30 to 5.33. In general, the Mooney-Rivlin plots for rubber networks exhibit a rectilinear relationship at high values of $1/\lambda$ (i.e. low λ values), with an upturn in the curves as $1/\lambda \rightarrow 0$ (i.e. at high λ values). This upturn is attributed to the onset of non-Gaussian behaviour (202,49). In the majority of cases, the curves at small $1/\lambda$, or high λ , show a monotonically increasing gradient, as shown by the WTC-NR plots. Smith et al (202) have shown that, under certain conditions, strain crystallizable rubbers such as NR can show distortions in the Mooney-Rivlin curve as $1/\lambda \rightarrow 0$. This is because of the onset of crystallization. When crystallization occurs, the curves are similar to those for the WTC-NR materials. However, with amorphous SBR based systems, strain induced crystallization cannot have occurred. The more likely explanation for this upturn behaviour is a debonding process. As this behaviour is associated with large strains, the process underlying this behaviour can best be examined using the large strain non-Gaussian plots given in Figure E.11, and Figures E.15 to E.20 (in Appendix E).

The simplified form of the inverse Langevin expression, equation 5.9, predicts that rubber networks should exhibit a linear relationship between $(1-1/\lambda)/\sigma$ and λ^2 at large extensions. This is seen for the unfilled SBR compound (i.e. with $\phi_{RR}=0$) in Figure 5.33. The continuous line terminate at the break point. Deviation from this conventional network behaviour can occur for several reasons, such as strain induced crystallization (202) and debonding between matrix rubber and small particulate reinforcing filler (203). Both these cases would result in the stress being less than the value expected for non-Gaussian behaviour, so that the plots would show a continuous decreasing negative gradient with increasing λ^2 . This curvilinear relationships are shown by both the WTC-NR and WTC-SBR systems in Figures 5.31 and 5.33. For compounds without crumb incorporation (hence debonding between matrix and particles cannot occur), amorphous SBR based vulcanizate showed a linear relationship as predicted by the non-Gaussian model, whereas a curvilinear plot was

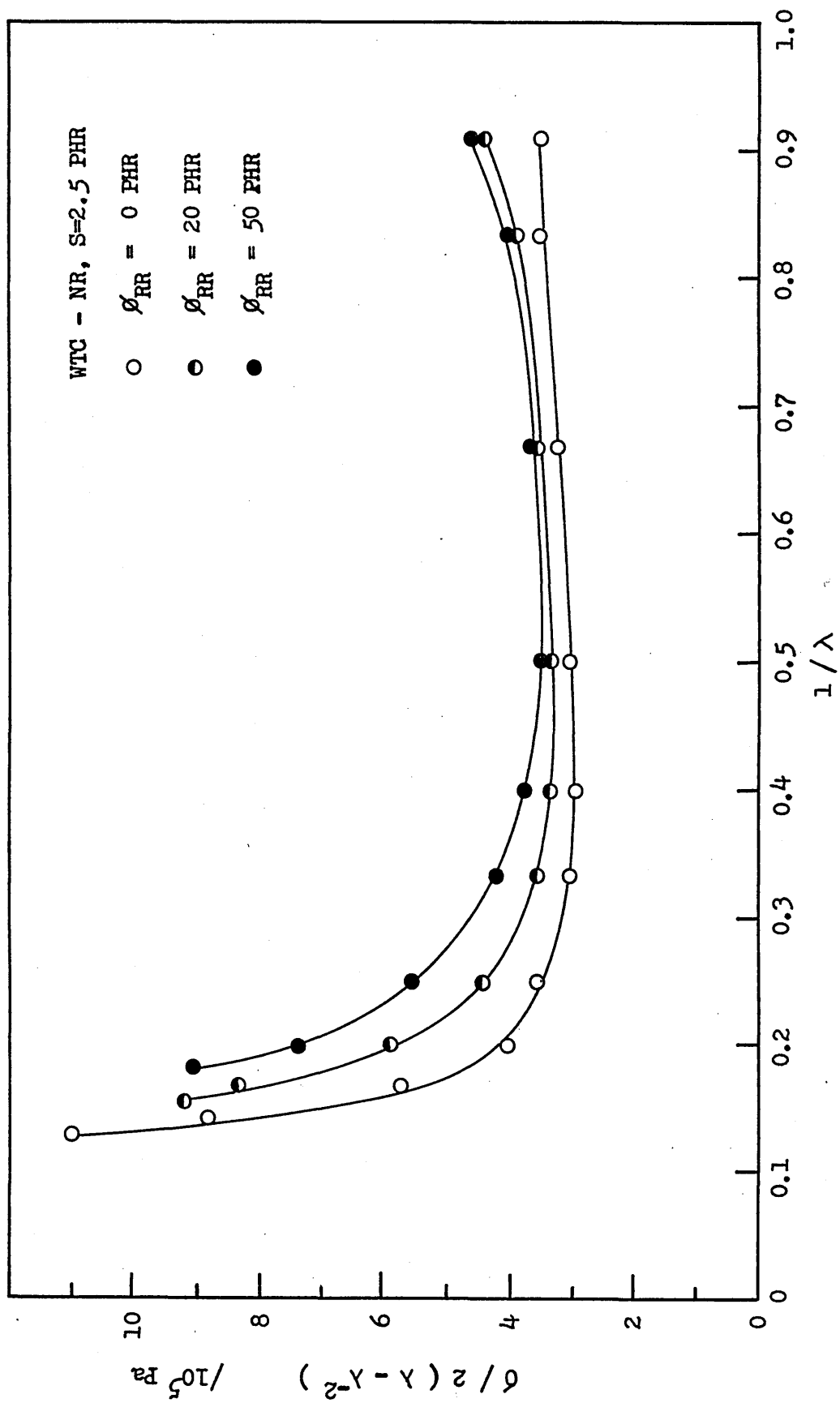


FIGURE 5.30 Mooney-Rivlin plots for WTC-NR composites with S = 2.5 phr.

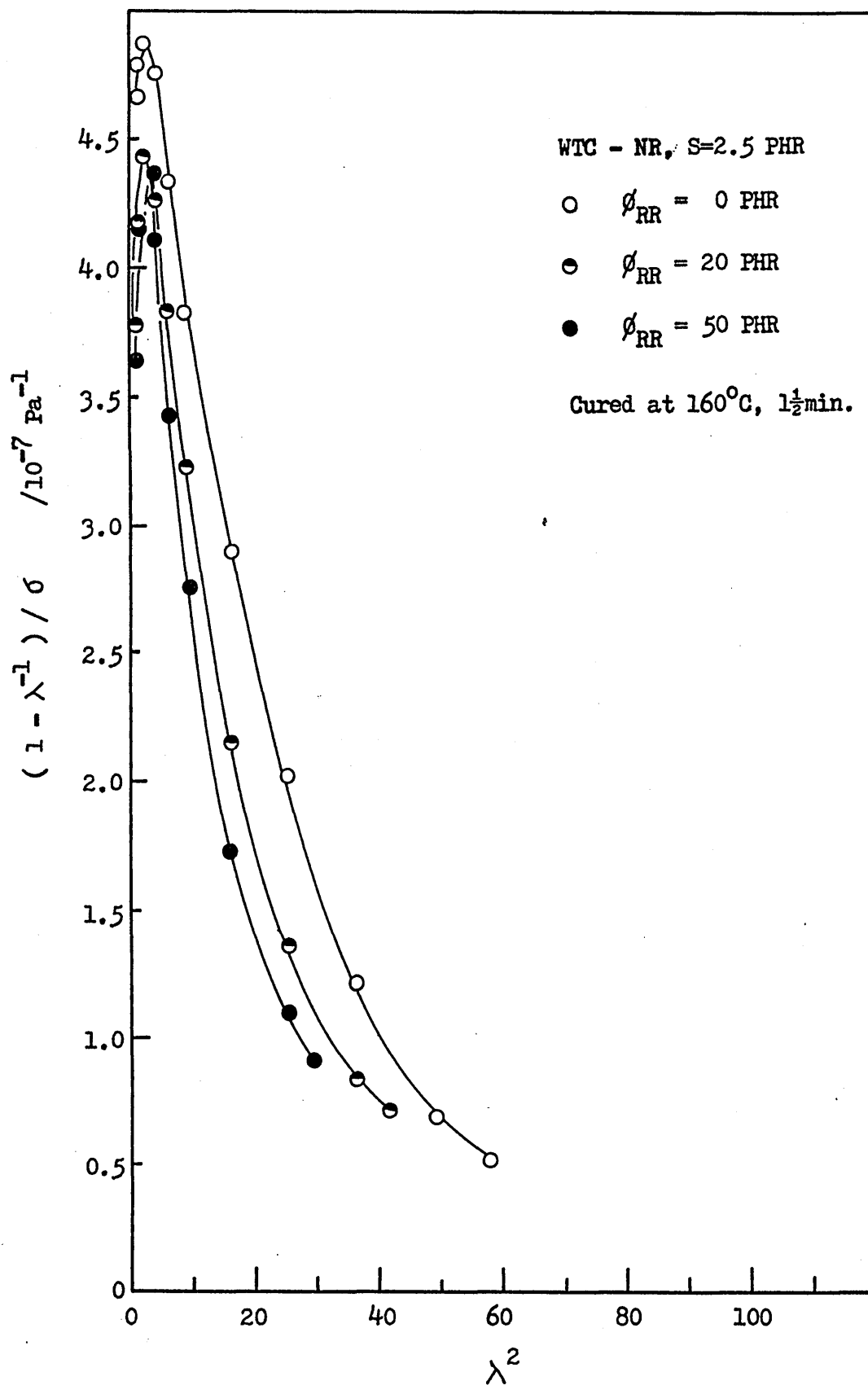


FIGURE 5.31 Non-Gaussian plots for WTC-NR composites with S = 2.5 phr.

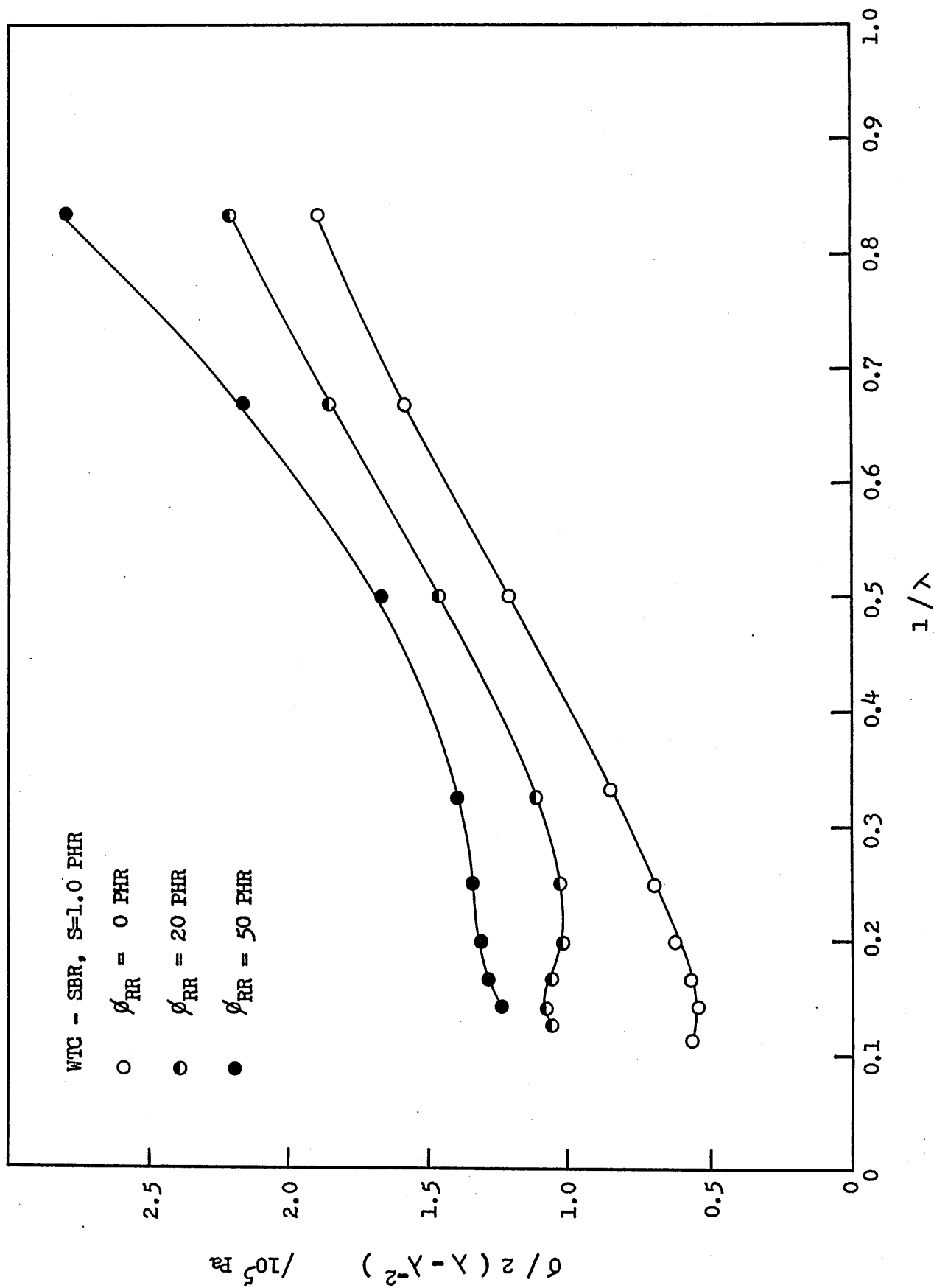


FIGURE 5.32 Mooney-Rivlin plots for WTC-SBR composites with $S = 1.0$ phr.

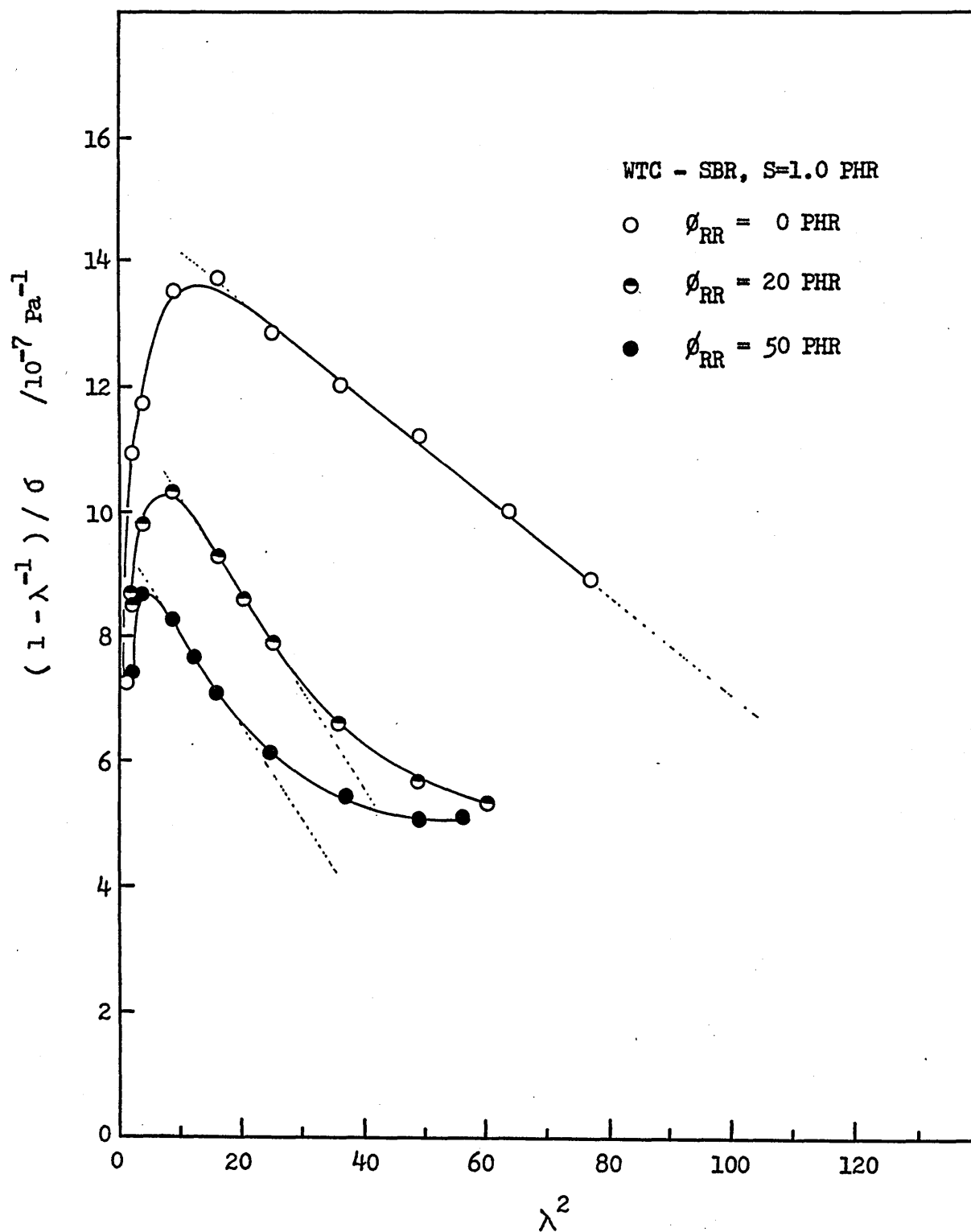


FIGURE 5.33 Non-Gaussian plots for WTC-SBR composites with S = 1.0 phr.

obtained for NR based compound. As debonding cannot have occurred, this curvilinear relationship can be attributed to the strain crystallizable characteristic of NR. With rubber crumb incorporation, debonding between matrix and crumb particles can occur when the composite is strained and when the applied stress is greater than the cohesive bonding strength between the matrix and crumb. Therefore, if debonding process occurs in an unreinforced, non-strain crystallizable matrix rubber (eg. SBR), and the onset of debonding is abrupt, it could give rise to a non-Gaussian plot which is rectilinear when the strain is below a critical strain for debonding, λ_K , and curvilinear when λ is above λ_K . This type of behaviour is exhibited by the WTC-SBR composites for sulphur contents in the range of 1.0-2.0 phr, but was not observed for S=5.0 and 10.0 phr composites. The values of λ_K for the WTC-SBR systems are presented in Table 5.2 together with λ_B , the extension ratio at break and σ_K , the stress at λ_K . Assuming that the interpretation of λ_K is correct, it can be concluded that, for $\lambda < \lambda_K$, the WTC-SBR composites behave like normal elastomeric networks exhibiting Gaussian and non-Gaussian type behaviour. At $\lambda \geq \lambda_K$, debonding between the matrix and the crumb particles takes place so that the stress transfer parameter, R, in equation 5.7 is less than unity. At high loadings of sulphur, S=5.0 and 10.0 phr, debonding does not appear to have occurred. This is because the $\lambda_K > \lambda_B$ for these composite materials.

From a technological point of view, λ_K for a composite is desirable to be large, since debonding will inevitably weaken the composite. It is seen from the data presented in Table 5.2 that, although λ_B for the WTC-SBR composites at a particular curative content do not differ greatly, λ_K decreases substantially with increasing ϕ_{RR} . This may impose a severe limitation on the amount of recycled rubber that can be incorporated into a rubber compound, especially for applications requiring large extensions. It is also seen that σ_K increases with increasing ϕ_{RR} , which may be related to the physical property enhancement characteristics of the WTC-SBR composites on crumb incorporation. Hence, although debonding occurs at lower extensions with increasing ϕ_{RR} , the stress at which debonding occurs is greater (than at smaller ϕ_{RR}). This, thus, presents a rubber technologist with an additional freedom in the designing of a crumb incorporated compound having a particular specifications.

A discussion of the mechanisms responsible for the shape of the stress-strain curves, and ultimately the failure process itself, can be made. At low and moderate strains, the WTC-rubber compounds show that rubber-particulate scrap rubber composites behave similarly with other rubber

networks exhibiting Gaussian and non-Gaussian behaviours. As mentioned above, the peculiarities in the $(\sigma_B)_C / (E_0)_C - \lambda$ curves for WTC-SBR systems might be associated in some way with the ratio of the Mooney constants C_2/C_1 . At low sulphur levels, where the difference in the $(\sigma_B)_C / (E_0)_C - \lambda$ plots at small values of λ for different ϕ_{RR} are the most apparent, the C_2/C_1 ratio is large (>5). For WTC-SBR systems with higher sulphur loadings, and also for WTC-NR systems, where the curves almost coincide, $C_2/C_1 \rightarrow 1$. This could perhaps be related to hysteresis, as the term C_2 is associated with hysteresis phenomenon (204) and that particulate recycled rubber vulcanizates have been reported to exhibit exceptional vibration isolation properties (205). An full explanation of this behaviour in terms of the network morphology cannot be given at present due to lack of appropriate data.

At large extensions, the debonding process plays an important role in determining the shape of the $\sigma - \lambda$ curves and the strength of the composites. Two mechanisms appear to be operative, both of which have been described by Eirich and Smith (133). These mechanisms are shown schematically in Figure 5.34, and may be classified as cavitation failure and debonding failure. In both cases, fracture results eventually from debonding between matrix and crumb particles. A number of factors influence the debonding process. The most important of these are probably the strength of the matrix rubber relative to the interfacial bond strength and the relative stiffness of the two material phases, and the volume fraction of recycled rubber crumb incorporated. Together, these factors govern the localised strain, and hence the stress within the matrix material. Microscopic studies of fracture surfaces, both optical and SEM have not provided any evidence of the fracture of the crumb particles themselves.

Two differing situations are presented in the WTC-rubber composites considered here. In both cases, the modulus of the matrix material is less than that of the rubber crumb (WTC), but for WTC-SBR systems, it is estimated that the strength of the matrix rubber is much less than that of the crumb whereas for WTC-NR systems, it is approximately the same. Debonding probably begins with cavitation in the matrix due to the triaxial tensile stress caused by the modification of the overall stress field by the relatively rigid crumb particles. The maximum stresses, which result in the creation of elliptically shaped voids or vacuoles, occur at some distance away from the particles (133), see

Figure 5.34. Increasing the strain will cause the propagation of a tear tip from the voids towards the crumb particle, resulting in debonding between the matrix-crumb interface. Strain energy is lost in debonding (201), and shows up as the concavity of the $\sigma - \lambda$ plots and the distortion of Mooney-Rivlin plots as $1/\lambda \rightarrow 0$. Further increase in strain leads to tear propagation through the matrix and eventually failure. With relatively high strength matrix rubber, such as WTC-SBR with S=5.0 and 10.0 phr, and WTC-NR composites, debonding probably occurs at the matrix crumb interface resulting in the formation of elliptical or conical voids (133, 207), with subsequent tear propagation through the matrix and failure. In this case, debonding and failure can take place simultaneously.

Table 5.2 Critical Strain and Stress for Debonding for WTC-SBR

SULPHUR CONTENT /phr	ϕ_{RR} /phr	λ_B	λ_K	σ_K /MPa
1.0	0	8.8	-	-
	20	7.8	5.4	1.1
	50	7.5	4.6	1.2
2.0	0	7.6	-	-
	20	5.6	5.2	1.4
	50	5.7	4.1	1.7
5.0	0	3.9	-	-
	20	2.8	$>\lambda_B$	-
	50	2.9	$>\lambda_B$	-
10.0	0	2.9	-	-
	20	2.2	$>\lambda_B$	-
	50	2.4	$>\lambda_B$	-

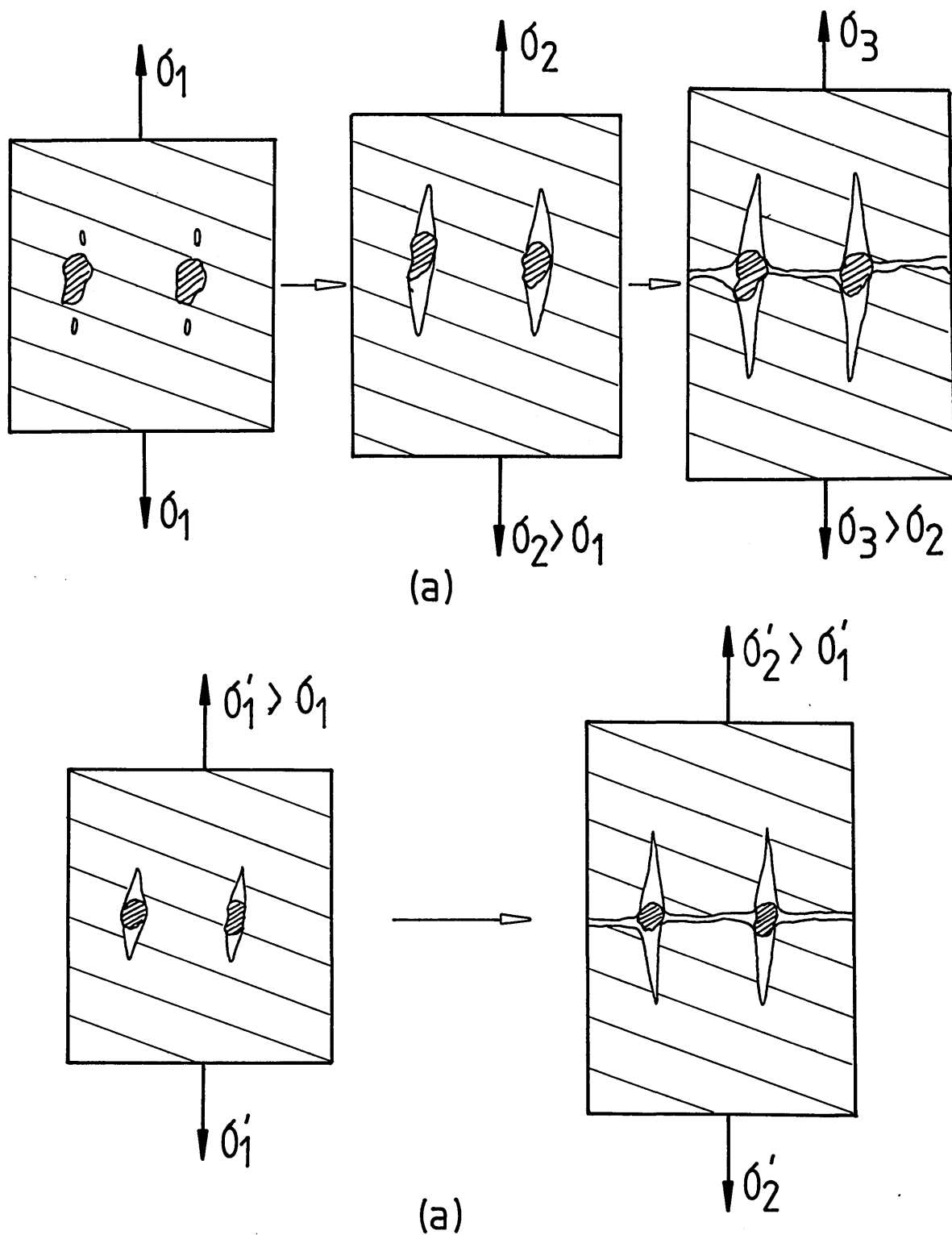


FIGURE 5.34 Schematic diagram of two failure mechanisms.

- (a) Cavitation with subsequent tear tip propagation and debonding between matrix and filler, and failure;
 (b) Dewetting between matrix and filler with subsequent tear tip propagation through matrix.

5.5 Conclusions

It was shown that the physical properties of a particulate scrap rubber incorporated rubber vulcanizate are largely dependent upon: (i) the effective particle size of the recycled rubber particles; (ii) the vulcanization system and (iii) the volume fraction of the incorporated recycled rubber filler.

Analysis carried out using data from Burgoyne et al (14) has shown that the effect of the particle size followed the Gent model

$$\frac{(\sigma_B)_C}{(\sigma_B)_m} = \left[\frac{T_C (E_O)_C}{T_m (E_O)_m} \right]^{\frac{1}{2}} \left[\frac{C_m}{d_{eff} + C_m} \right]^{\frac{1}{2}} \quad (5.3)$$

where T_C and T_m are tear energies of the vulcanizate and the matrix respectively, d_{eff} the effective particle diameter, and C_m is an inherent flaw size characteristic to the matrix rubber compound.

Our investigation has shown that the initial modulus, $(E_O)_C$ and tensile strength, $(\sigma_B)_C$ of our WTC-SBR vulcanizates, in general, increased with increasing amount of WTC recycled rubber incorporation, ϕ_{RR} . This indicates that $(E_O)_C$ and $(\sigma_B)_C$ can be enhanced by incorporating WTC. This is in contradiction to the general observation in other recycled rubber filled vulcanizates, and is thought to have due to the very low property values of the matrix compound and bonding between particle and matrix.

It was also shown that these particulate scrap rubber incorporated rubber vulcanizates can be considered as rubber-rubber composites. The strength property relationships of the WTC-SBR composite systems, and the TCR filled systems are found, in general, to follow a particular form of the simple law of mixtures model

$$(E_O)_C = (E_O)_m (1-V_{RR}) + R (E_O)_{RR} V_{RR} \quad (5.6)$$

$$(\sigma_B)_C = (\sigma_B)_m (1-V_{RR}) + R' (\sigma_B)_{RR} V_{RR} \quad (5.7)$$

where the reinforcement parameters, R and R' have a value between zero and unity. Discrepancies from the model were thought to have due to the many factors that have influenced the properties of the composites.

One of the important factors is the interference of the vulcanization process with the incorporation of particulate (vulcanized) rubber crumb into a rubber compound. This curative migration phenomenon is studied in detail in the next Chapter.

The effect of curative migration from the matrix rubber compound into the rubber particles is to lower the strength properties of the composite systems. This has been observed for all the rubber composite system considered.

The mechanics of the WTC incorporated vulcanizates have been studied using the stress-strain behaviours of these composites. The stress-strain relationships of these material systems, in general, are similar as those for normal elastomeric vulcanizates, exhibiting Gaussian and non-Gaussian behaviours, debonding between matrix and particulate filler and strain induced crystallization. The Mooney-Rivlin model has been used for low extension Gaussian behaviour, and a non-Gaussian model based on the inverse Langevin function has been used for high extensions.

The deviations from the Mooney-Rivlin plots and the non-Gaussian plots for high extensions, for WTC-SBR composites, are attributed to the onset of the debonding process. At low sulphur contents, range between 1 - 2 phr, a critical strain for debonding, λ_K , can be obtained from both the Mooney-Rivlin and non-Gaussian plots. Below this critical strain for debonding, i.e. $\lambda < \lambda_K$, the material systems behave like normal elastomeric networks exhibiting Gaussian and non-Gaussian type behaviour. At $\lambda \geq \lambda_K$, debonding between the matrix and particles takes place, and the material systems exhibit a curvilinear non-Gaussian behaviour. At high sulphur vulcanizing agent levels (5 and 10 phr), the breaking strains are less than λ_K , hence these two composite systems did not exhibit curvilinear non-Gaussian behaviour.

It is thought that the hysteresis phenomenon has given rise to the peculiar behaviour of the stress-strain relationships at low strain values for WTC-SBR composites (at low sulphur levels), through the Mooney constant C_2 . At high extensions, the shape of the stress-strain curves is determined to a large extent by the debonding process. Two failure mechanisms are proposed to have been in operative for these composite systems. The cavitation failure mechanism initiates with voids or vacuoles formation in the weak matrix some distance away from the

filler particles due to the high triaxial tensile stress. These vacuoles subsequently propagate to the matrix-particle interfaces and effecting debonding between matrix and the particles which eventually failure. For WTC-SBR composites with low sulphur levels of 1 - 2 phr, failure has probably occurred through this cavitation mechanism.

In the debonding failure mechanism, debonding at the matrix-particle interface initiates the failure process, with subsequent tear tip propagation through the matrix and failure. In this case, debonding and failure can take place simultaneous. WTC-SBR with sulphur levels of 5 and 10 phr, and WTC-NR composite materials probably follow this failure mechanism.

6.1 General Consideration

The phenomenon of curative migration/diffusion and redistribution within rubber blends and rubber compounds containing vulcanized particulated rubber is well known (eg. Gardiner (190, 191), Guillaumond (192), Bhowmick & De (193), Swor et al (27), Grebenkina et al (160) and Polyakov et al (24)). The occurrence of curative redistribution in these rubber material systems has resulted in the vulcanizates of these composites having an inferior physical properties to that of the base rubber/s. Although curative diffusion seems to be central to the properties of rubber-rubber composites, little relevant experimental data has been presented. The work of Grebenkina et al etc discussed below, was confined to model systems consisting of planar sheets of rubber. There has been no report of the quantitative distribution of curing agent in rubber vulcanizate-recycled rubber crumb compounds. Our investigations have provided quantitative data. However their exact meaning is not certain, as explain below.

The crosslink density of a rubber network is determined primarily by the concentration and type of curatives presence in the rubber compound (72, 135). The physical properties of a rubber vulcanizate, in turn, depend upon the crosslink density of the vulcanizate (see for example Figure C.6 of Appendix C). Consequently, the migration of curative is of prime important in determining the physical properties of a rubber vulcanizate. The main objective of this investigation was to study the distribution of sulphur within a rubber-rubber crumb composite. The influence of the cure system, and the type of rubber, on the relative distribution of sulphur in the rubber crumb, and the matrix were also examined. It was intended that this study would assist in identifying the mechanism causing the detrimental change in physical properties with such composite systems. It should, however, be appreciated that the present investigation is only a preliminary probe into the curative redistribution study in such material systems. More detailed systematic studies are needed to thoroughly investigate and predict this important behaviour.

Electron microscopy is a well established analytical technique in a wide diversity of scientific fields such as metallurgy, physics,

electronics, mineralogy, material sciences and biology. Electron microscopic analyses have also been used in polymer science and technology mainly as a qualitative analytic tool and a means of studying the morphology of the specimens (eg. Kruse (198) and Engel et al (199)). Four widely used analytical electron microscopic techniques have been employed in our study of the distribution of sulphur in the material systems. They are :

- a) secondary electron imaging ;
- b) X-ray elemental mapping ;
- c) X-ray elemental line scan ;
- and d) point-to-point analysis.

A brief introduction of the operations of the SEM is presented in Appendix F.

The investigations were carried out using a Philips PSEM 500 Scanning Electron Microscope equipped with EDAX and EDIT facilities. (Energy Dispersive Analysis of X-rays, EDAX allows instant identification of elements present. EDIT facility, used in conjunction with an online microcomputer, allows the various corrections to be made to the detected X-ray spectrum).

6.2 Previous Work

The study on the physical properties of vulcanizates incorporating vulcanized rubber crumb has shown, in general, properties deteriorate with the introduction of rubber crumb (see Chapter Five). Swor et al (27) have shown that to achieve optimum physical properties with such material systems, it is necessary to increase the amount of curing agent in the base rubber mix. Gardiner (190, 191), Woods and Davidson (194), Baranwal and Son (195) and other workers (192,193,197) working on rubber blends, have studied the ways in which curatives diffuse/migrate selectively and characteristically from one rubber to another. As a result, the physical properties of these rubber blends are affected, causing difficulties in processing blends especially in rubber products consisting of different rubbers. Covulcanizing of layers of different rubber compounds in a tyre is an example. Gardiner (190) has proposed that the driving force for the migration of curatives is the relative solubility of the curatives in the rubbers, and that curative migration can still occur in the direction of the rubber of greater unsaturation even when the solubilities of the curatives in the two

rubbers are similar. Gardiner has attributed the loss in physical properties of rubber blends to a curative depleted zone at the interface which resulted in an undercured region. Gardiner has also shown that the distance of curative migration from the interface can be calculated using a modified form of Einstein's equation for Brownian motion :

$$\bar{X} = (DT)^{\frac{1}{2}}$$

where \bar{X} is the distance the curative can diffuse in a given length of time, T, and D is the diffusion coefficient of the curative between two rubbers.

Grebenkina et al (160) have investigated specifically the distribution of sulphur in a three layered model system consisting of a vulcanized middle layer being sandwiched between two unvulcanized mix. One of the vulcanizate-mix interface is separated by a sulphur impermeable cellophane film. All three layers are of the same carbon black-loaded, polybutadiene-based compound formulation. Their investigation showed that an equilibrium sulphur distribution is established in a relatively short time (about 10 minutes in one of their experimental runs). They showed that the migration of sulphur depends on the difference in free sulphur concentrations in the phases (note free sulphur concentrations and not total sulphur concentrations). Figure 6.1, constructed from data presented by Grebenkina et al, illustrates this point. They proposed that as vulcanization takes place, the shorter crosslinked and less mobile molecular chain segments seem to be able to retain the free sulphur molecules and hence increasing the rate of crosslinking. They attributed the latter to an apparent lowering of activation energy in sulphur crosslinking reactions.

Most studies on the curative migration in a rubber compound are carried out with blends of two or more incompatible rubber types (eg. SBR and EPDM), hence are not particularly relevant. As mentioned above, there have been no reports of direct quantitative measurement of the distribution of curative in recycled rubber crumb composites.

6.3 Experimental Procedure

As described in Appendix F, there are a wide variety of electron-solid interactions, and that these interactions are dependent not only upon the composition of the sample studied, but also the operating conditions,

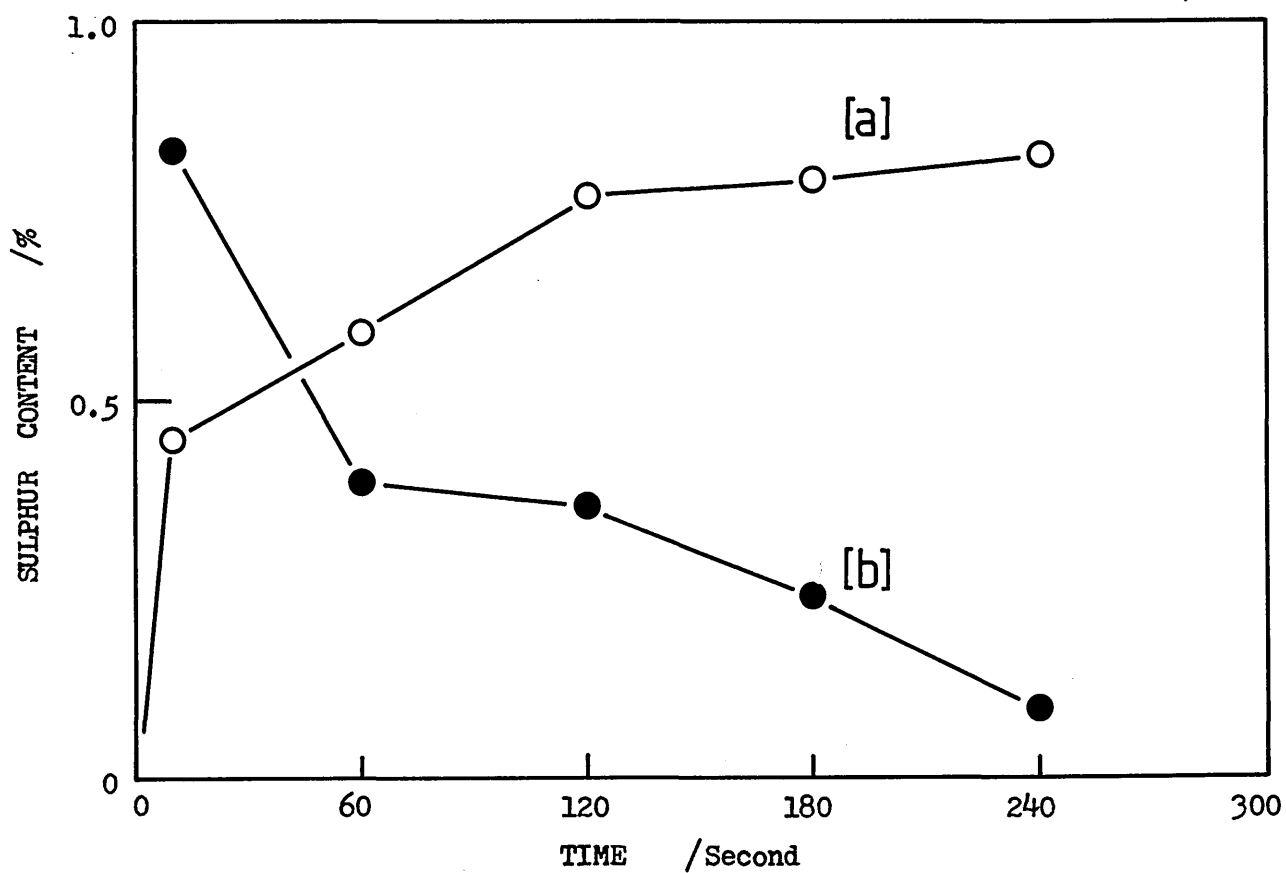


FIGURE 6.1 Variations of sulphur content as a function of time of vulcanization. (a) Increase in total sulphur content in the vulcanizate; (b) Difference in free sulphur contents between mix and vulcanizate. (data from Grebenkina et al (160)).

the sample topography and preparation, and the selected mode of the scanning electron microscope. Since the present semiquantitative investigation is concentrated on the study of sulphur, the experimental procedure is made more simple in that the operating conditions are selected to concentrate on the sulphur peaks of the EDAX spectrum.

Consistency in the experimental procedure was the main concern. Although utmost care was taken to ensure such consistency, there were areas which were beyond the control of the operator. One such area was the variation in electron beam current over the whole experimental period (of several weeks). The electron beam current is governed by the filament current, and the filament which generates the electrons is being consumed through usage. Hence, a higher filament current is required to generate a beam of electrons of the same current. Unfortunately, on the SEM used, it was not possible to select a particular saturated filament current, although care was taken to ensure that saturated filament currents of similar magnitudes were used throughout. The consequence of this variation is that quantitation comparison cannot strictly be made between the results obtained in different experimental runs.

The investigation was carried out with samples of vulcanizates incorporating rubber crumb as used in the physical properties investigation. These vulcanizates have recycled rubber crumb loadings of 0, 20, and 50 phrs (parts per hundred rubber), sulphur contents of 1, 2, 5 and 10 phrs with SBR and NR as the matrix rubber ($S = 2.5$ phr for NR). Details of the compound formulations and vulcanizing conditions are given in Appendix E.

a) Specimen Preparation

The tensile testing sheets for the physical property investigation have been used to prepare the SEM specimens. The thickness of the specimen has been determined experimentally using a wedge shaped specimen. It is found that a thickness of 5 mm will sufficiently prevent the captured volume of the electron beam from interacting with the aluminium mount (see footnote at end of this section).

The rubber vulcanizate samples were cut from tensile sheets with a sharp razor blade, thus exposing the embedded rubber crumb particles. The specimens, having dimensions of 5 mm (height) by about 2 mm (width) by

about 10 mm (length, slightly different length was used to differentiate vulcanizates of differing rubber crumb loadings), were stuck in groups of three, according to the sulphur content, to an aluminium stud using SILVER DAG (tradename, a Colloidal Silver). The essential requirement was to ensure that the surfaces were as level as possible and that the thicknesses must be 5 mm. All the SEM specimens were then coated with carbon, at the same time to reduce additional variation in carbon coating thickness, by vacuum deposition. The sample assembly is shown schematically in Figure 6.3.

b) SEM Operating Conditions

A set of operating conditions was selected or determined experimentally, and, as far as practically possible, adhered to. This was to ensure experimental consistency. However, due to circumstance beyond the operator's control, the electron beam current cannot be kept constant throughout the experiment (as explained earlier, due to the construction of the SEM used). The operating conditions used with the Philips PSEM500 SEM were as followed (some of these settings were required by the EDIT calculations);

- a) the specimen angle was set at zero as marked on the tiltable door of the vacuum chamber (required by EDIT);
- b) the X-ray detector was positioned at 1 cm from the specimens (required by EDIT);
- c) the aperture setting of the electron beam condenser system was fixed at a particular optimum value;
- d) the spot size was set at $0.125\ \mu\text{m}$;

NOTE

After setting up the appropriate operating conditions, the slant edge of the wedge was adjusted so that it was perpendicular to the electron beam. This levelling was carried out using the focusing device of the microscope. An X-ray spectrum was obtained. With the centroid window (which selects the range of X-ray energies) set at a fixed width (hence the range) on the background signal next to the sulphur peak, the background counts within the fixed energy range for 80 seconds were obtained along known positions on the wedge. At least three readings were taken for each position so as to reduce statistical error. These background signal counts and their corresponding positions (and hence the thickness at that position) were plotted in Figure 6.2. It can be seen from this graph that saturated background count was reached after about 3.5 mm (given the statistical nature of the count collection process in the EDAX). The rather high background count at about 1 mm could be due to the backscattered electrons and other signals from aluminium stud which further interacted with the rubber and generating a high count. This gave an indication that the electron beam had created a captured volume which had interacted with the aluminium stud.

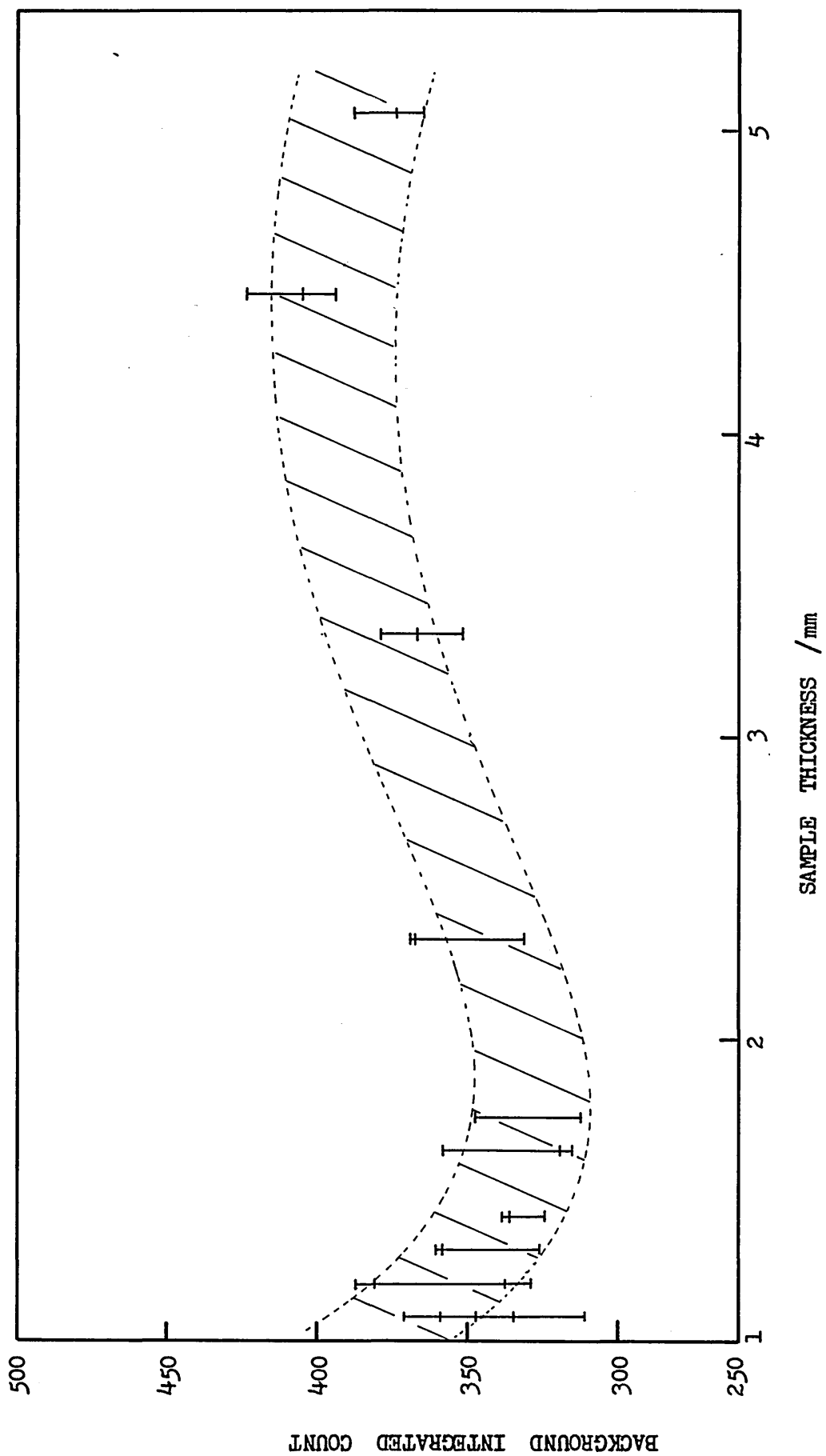


FIGURE 6.2 Background integrated count for 80 seconds as a function of the thickness of the sample.

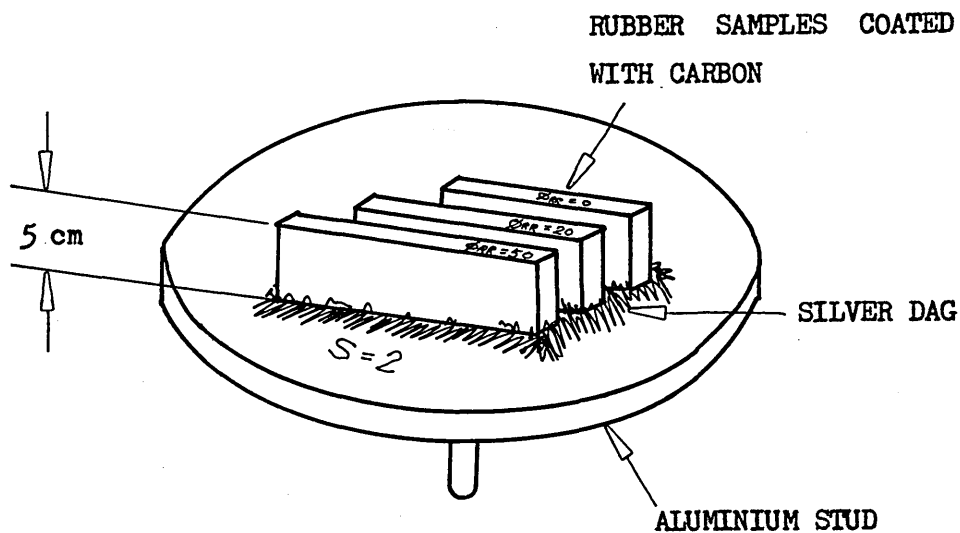


FIGURE 6.3 Schematic diagram of the assembly of rubber samples with three rubber crumb loadings at a particular sulphur level.

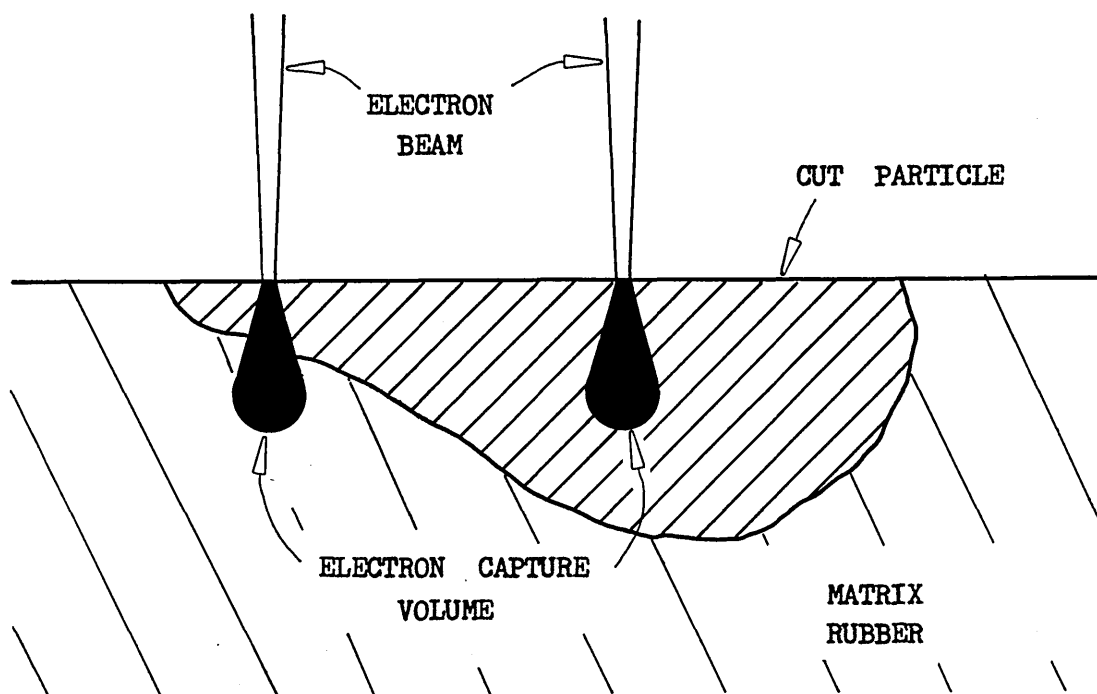


FIGURE 6.4 Schematic diagram for a cross-section of a cut rubber crumb particle showing electron capture volumes. Note that one of the electron capture volume extends beyond the particle.

- e) the electron beam accelerating voltage was set at 12 kV (calculated to optimise on sulphur peaks. E_c , the critical excitation potential for sulphur K_α emission line was estimated to be 2.48 kV, see Appendix F. Required practical accelerating voltage, $E_o = 2.7 E_c \doteq 6.7$ kV, i.e. E_o must not be less than 6.7 kV. Therefore 12 kV was selected for it was the next higher setting after 6 kV setting.);
- f) the emission switch was set at mark 2 ;
- and g) the filament current was adjusted to give an optimum saturated level.

Apart from the basic requirements by the material and the EDIT facility, the operating conditions were selected for an optimised situation, while ensuring that the yield (of X-ray signals) was sufficiently high, but at the same time prevent excessive penetration of the electron beam into the basically rubber hydrocarbon sample.

As mentioned above, the variation in beam currents from experimental run to run would impair the accuracy of the inter-run sulphur peak (sulphur K_α line integrated intensity count, see footnote) comparison. However, since a set of three samples with the same sulphur content but with 0, 20 and 50 phr loadings of rubber crumb was mounted on a same specimen holder, comparison among the sulphur intensity values of the samples within one run may be made.

One major problem in maintaining consistency occurred not only in inter-runs but also in intra-runs. This concerned the topographical effect of the cut surface especially samples loaded with rubber crumb. It was found that, perhaps due to differences in hardnesses, the rubber crumb particles tended to rise slightly, especially at particle-matrix interface. Care had been taken to select a particle with as smooth a surface as possible.

The capture volume effect of the electron beam caused concern in the selection of the particle, and its position in the sample. From the

FOOTNOTE

The terms sulphur peak, sulphur count, sulphur intensity value used interchangeably in the text are referring to the sulphur K_α line integrated intensity counts which has an energy of 2.307 keV.

result of the wedge experiment, it may be inferred that the capture volume of the electron beam may have extended through some parts of a cut particle as shown in the Figure 6.4. The sulphur intensity counts may, therefore, depend on both the sulphur concentration in the crumb particle as well as that in the matrix. The extend of this interference may vary from position to position.

The four techniques of Energy Dispersive Analysis of X-rays (EDAX) were well documented (see for example Russ (EDAX) (177, 178)). Firstly, a suitably smooth surface was selected. A secondary electron image was taken with the micrometer marker set on a line which subsequently used as a position marker for the X-ray line scan and the point-to-point analysis. X-ray sulphur distribution map of the surface of interest was then obtained with centroid set at sulphur $K\alpha$ line energy of 2.307 keV with very narrow window width. The centroid width determined the range of X-ray energies to be counted. A line scan was then taken with similar centroid setting. The line scan had a main drawback of including the background in its sulphur counts. A point-to-point analysis for the sulphur counts was carried out with the points positioned along known spots on the micrometer marker. The sulphur counts obtained by this analysis were the net sulphur counts with the background signals deducted. This "stripping" process was carried out using the online microcomputer equipped with EDIT facility (EDIT is a purpose written program package to use inconjunction with the EDAX facilities).

6.4 Results and Discussion

Representative examples of the SEM micrographs X-ray sulphur maps and X-ray sulphur line scans are given in Figures 6.5 through 6.8. The point-to-point analysis for elemental sulphur are presented in Figure 6.9 to 6.14. The X-ray sulphur maps present the sulphur distribution within the regions of interest which are shown in the corresponding micrographs. The sulphur line scans and the point analyses, taken along the micrometer marker lines indicated on the micrographs, show the relative concentration of sulphur along the lines of interest. The point-to-point analysis is believed to give more accurate results than the X-ray line scans, as explained earlier. Hence, the intensity counts obtained from the point-to-point analysis can be regarded as those due to the presence of elemental sulphur. This, however, may not strictly true, as errors may have been introduced through various undesirable electron/X-ray - solid interactions. A ZAF correction may be performed.

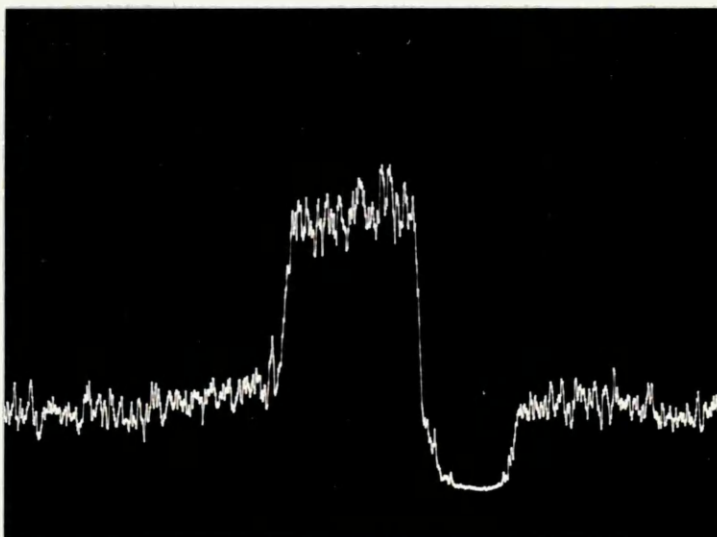
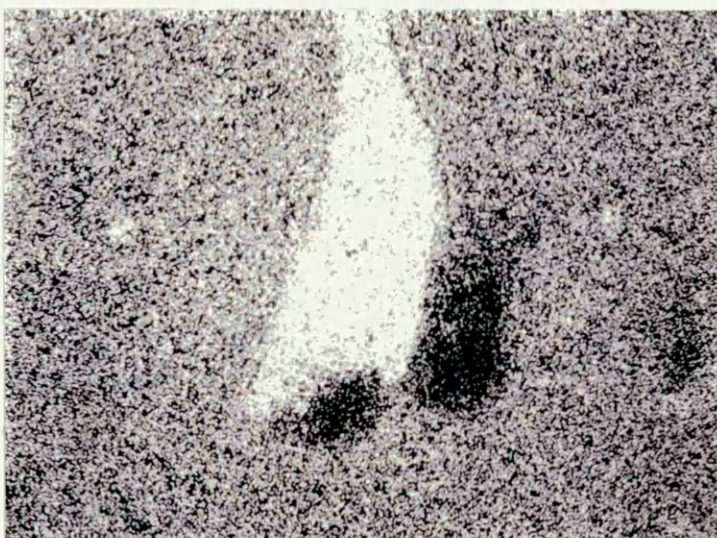
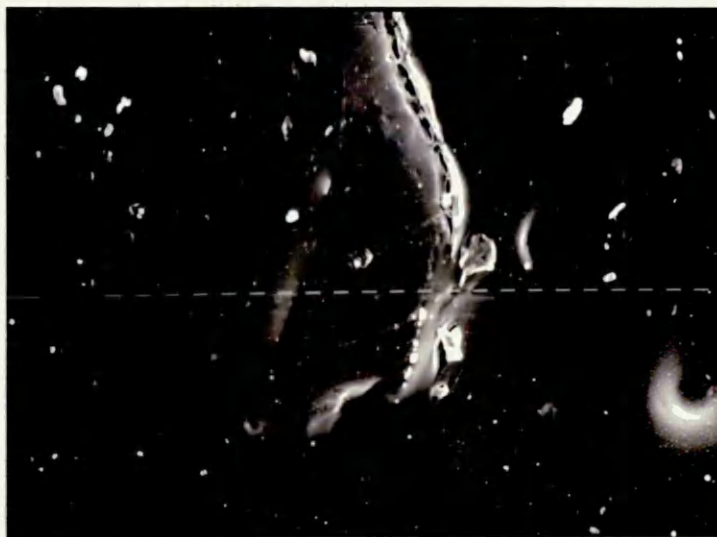


FIGURE 6.5 Results of SEM and EDAX sulphur migration study for WTC-SBR composites with $S=1$, $\phi_{RR}=20$ phr. (a) Photomicrograph; (b) X-ray sulphur map; and (c) X-ray sulphur line scan.

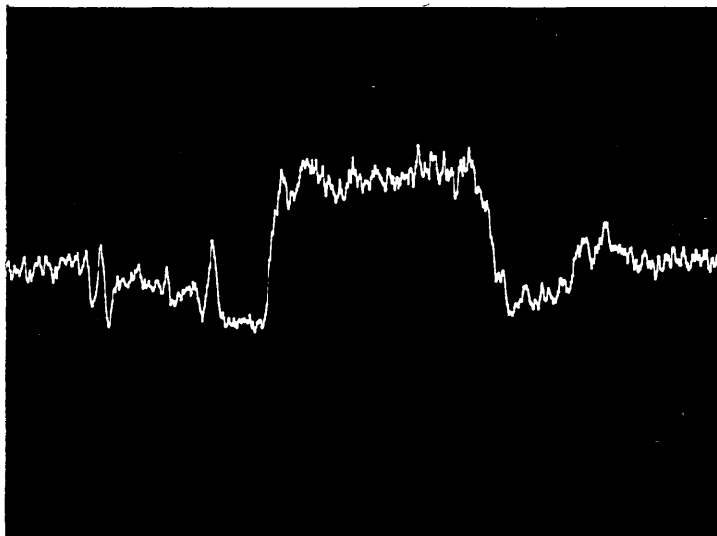
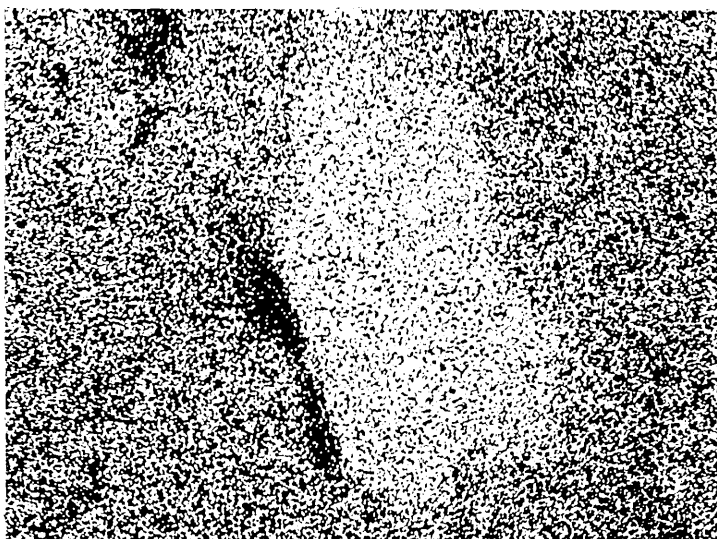


FIGURE 6.6 Results of SEM and EDAX sulphur migration study for WTC-SBR composites with $S=1$, $\phi_{RR}=50$ phr. (a) Photomicrograph; (b) X-ray sulphur map; and (c) X-ray sulphur line scan.

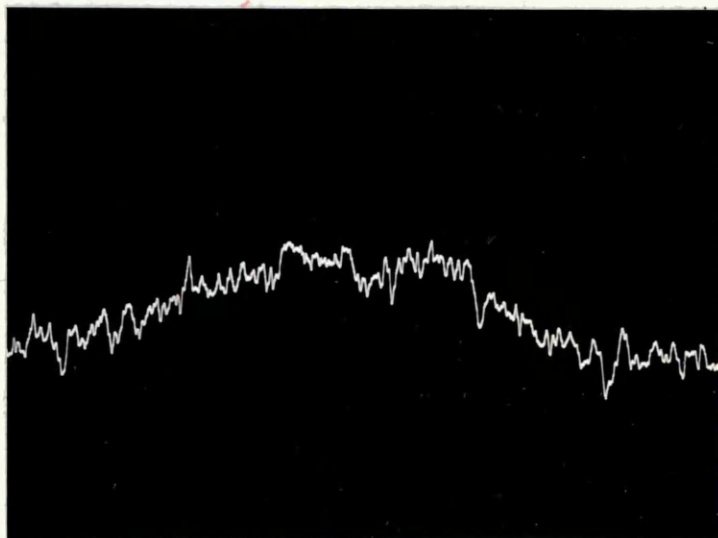
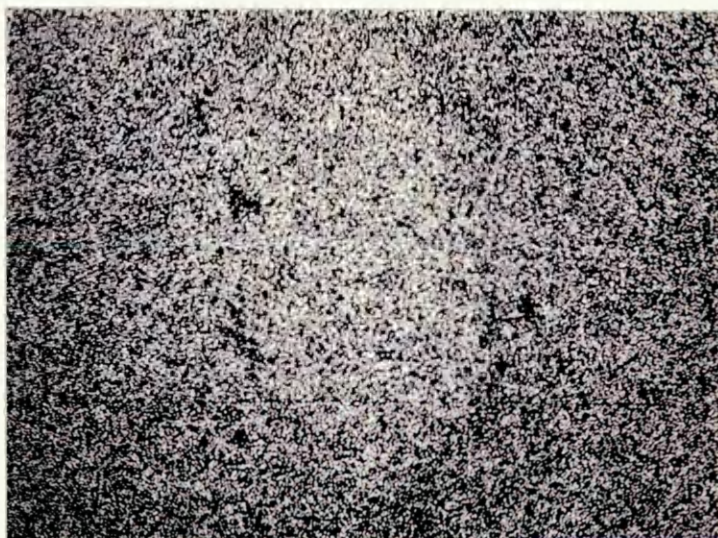
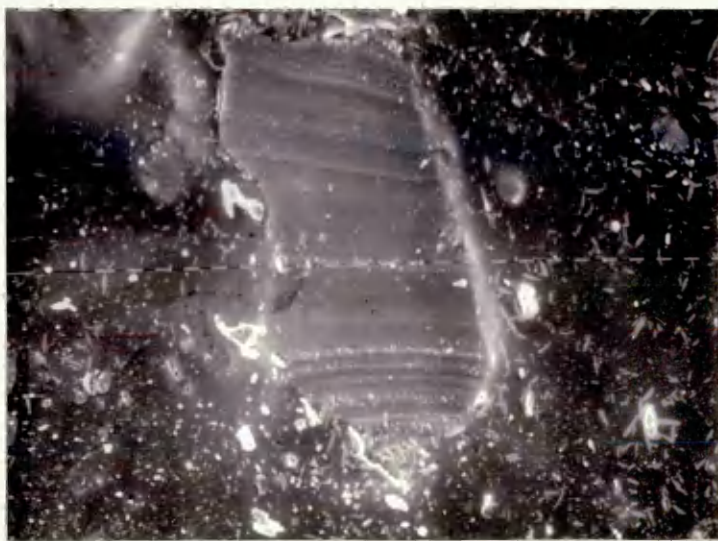


FIGURE 6.7 Results of SEM and EDAX sulphur migration study for WTC-SBR composites with $S=10$, $\phi_{RR} = 20$ phr. (a) Photomicrograph; (b) X-ray sulphur map; and (c) X-ray sulphur line scan.

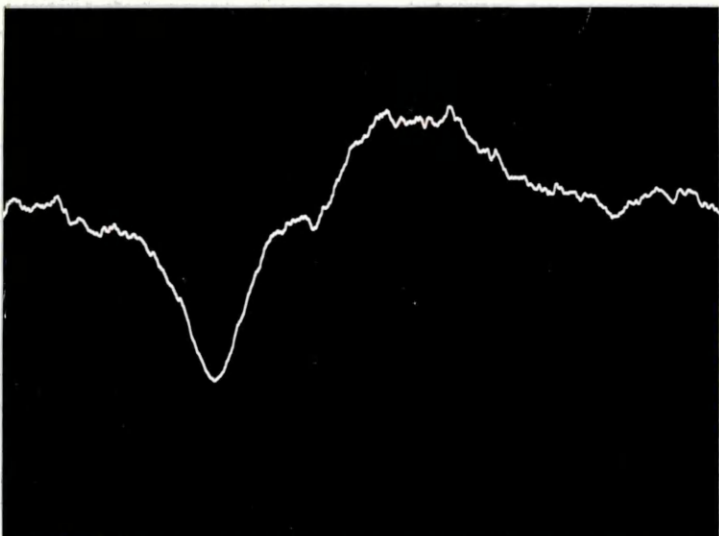
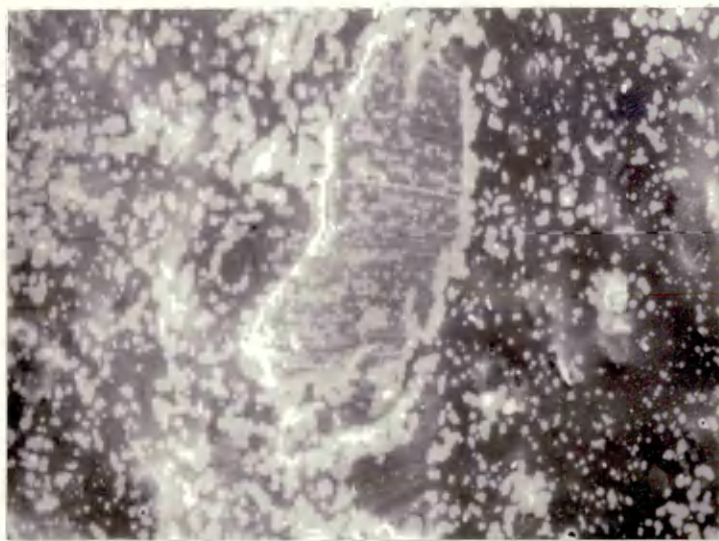


FIGURE 6.8 Results of SEM and EDAX sulphur migration study for WTC-SBR composites with S=10, $\phi_{RR} = 50$ phr. (a) Photomicrograph; (b) X-ray sulphur map; and (c) X-ray sulphur line scan.

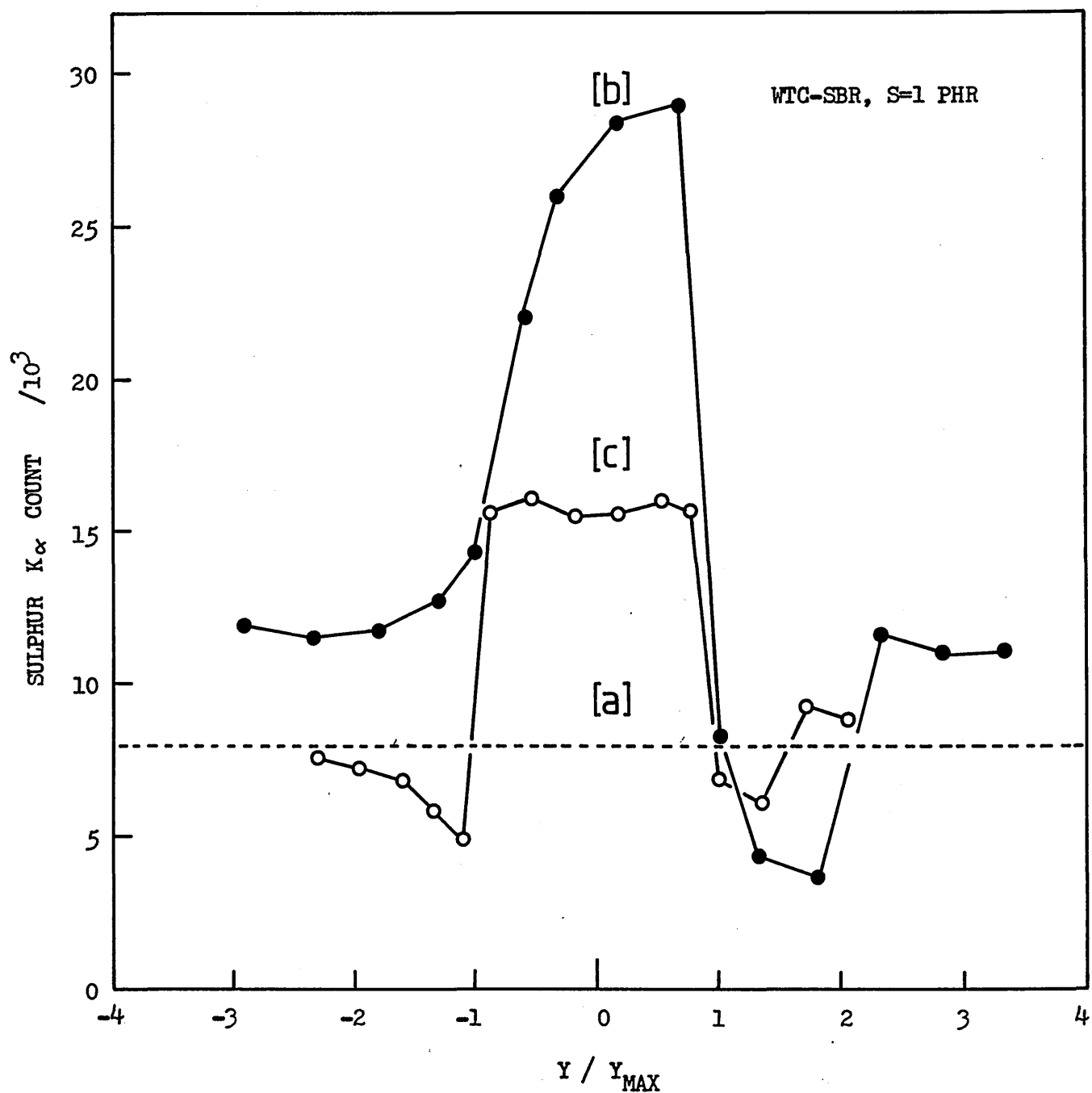


FIGURE 6.9 Variation of integrated sulphur $K\alpha$ peak count obtained by point analysis as a function of the distance from the centre of the crumb particle for WTC - SBR, $S = 1$ phr. (a) $\phi_{RR} = 0$; (b) $\phi_{RR} = 20$, $2 Y_{MAX} = 120 \mu m$; (c) $\phi_{RR} = 50$, $2 Y_{MAX} = 170 \mu m$.

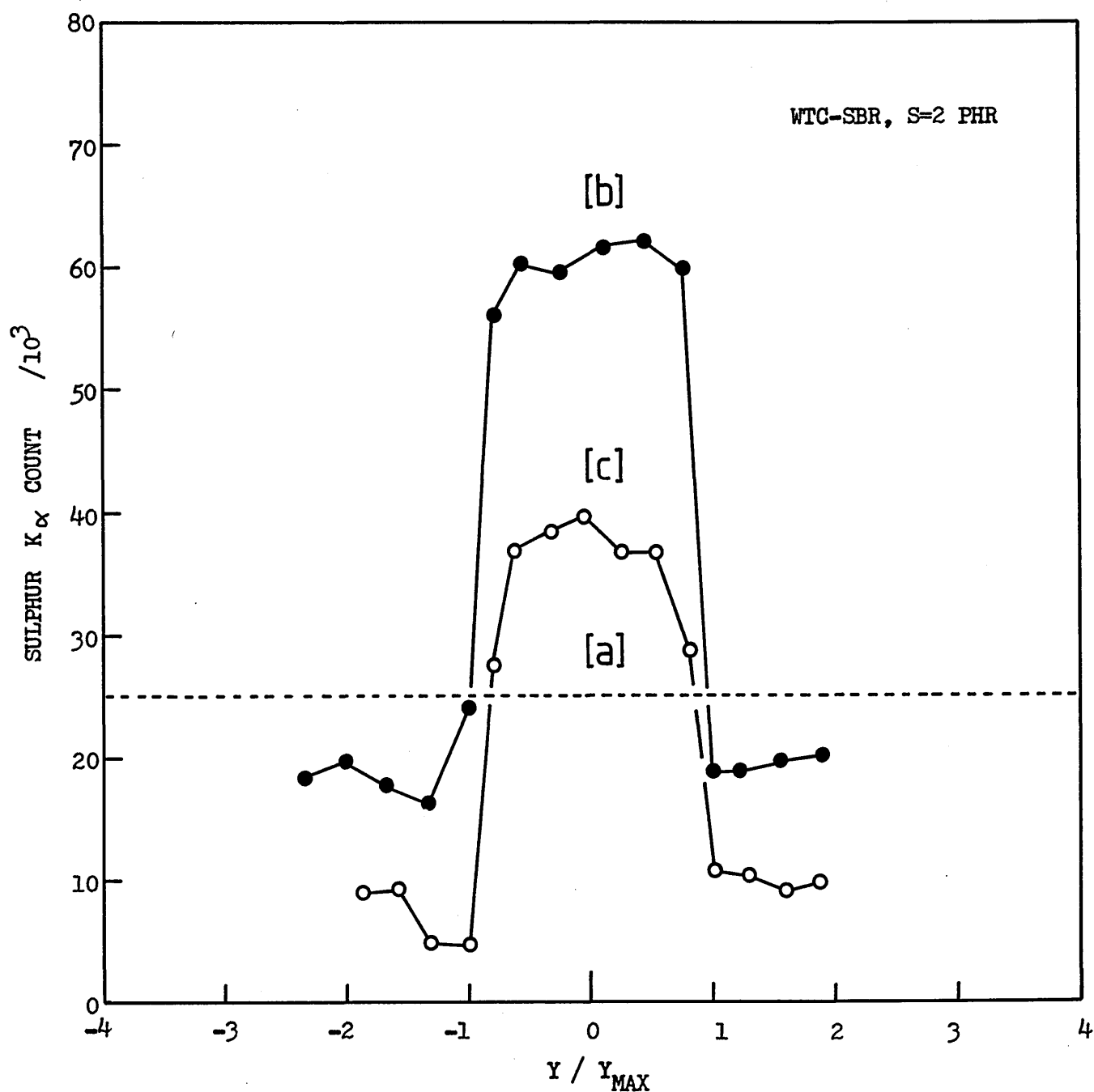


FIGURE 6.10 Variation of integrated sulphur K_{α} peak count obtained by point analysis as a function of the distance from the centre of the crumb particle for WTC - SBR, S=2 phr. (a) $\phi_{RR} = 0$; (b) $\phi_{RR} = 20$, $2 Y_{MAX} = 180 \mu\text{m}$; (c) $\phi_{RR} = 50$, $2 Y_{MAX} = 210 \mu\text{m}$.

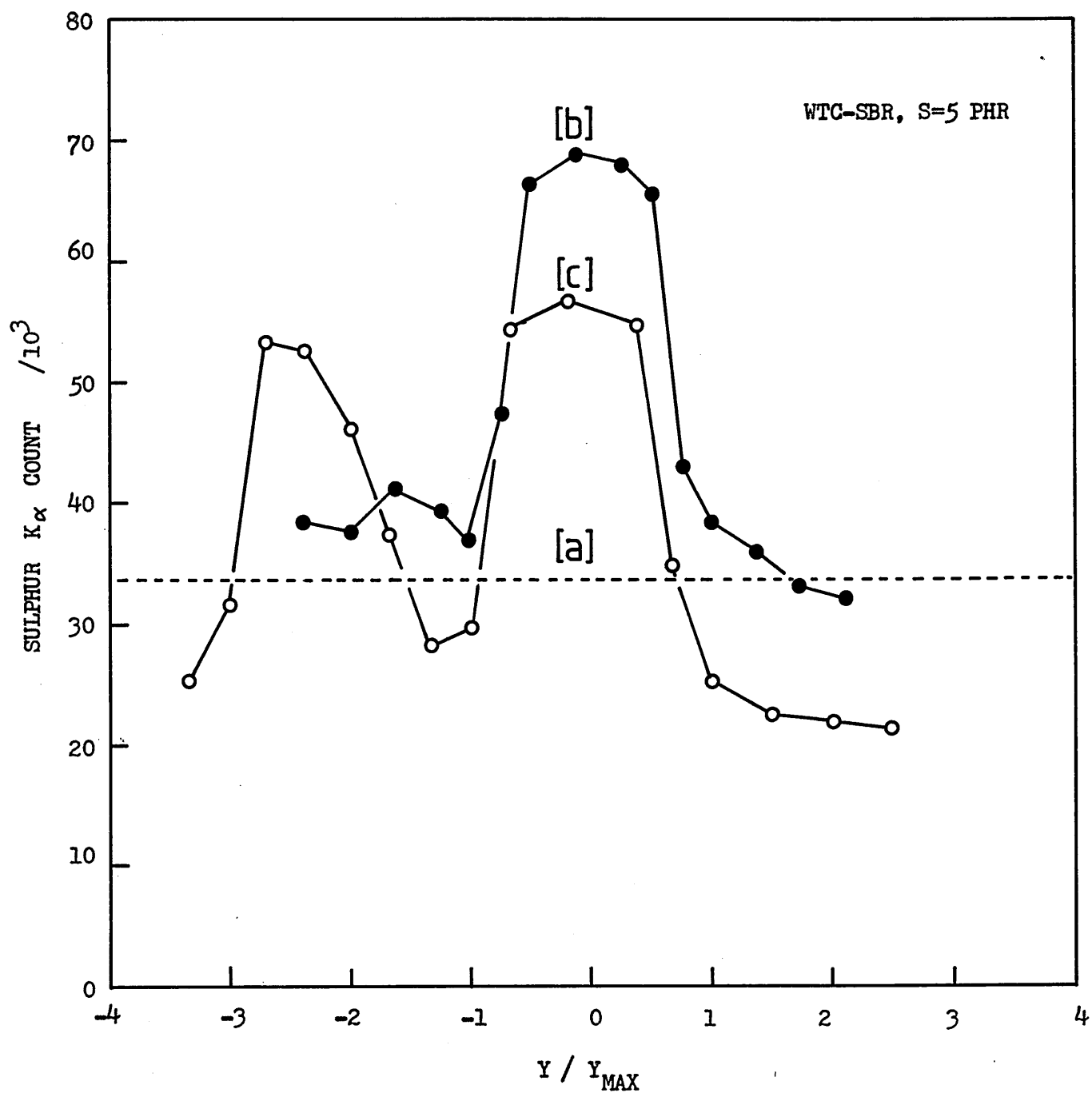


FIGURE 6.11 Variation of integrated sulphur K_{α} peak count obtained by point analysis as a function of the distance from the centre of the crumb particle for WTC - SBR, S=5 phr. (a) $\phi_{RR} = 0$; (b) $\phi_{RR} = 20$, $2 Y_{MAX} = 160 \mu\text{m}$; (c) $\phi_{RR} = 50$, $2 Y_{MAX} = 120 \mu\text{m}$.

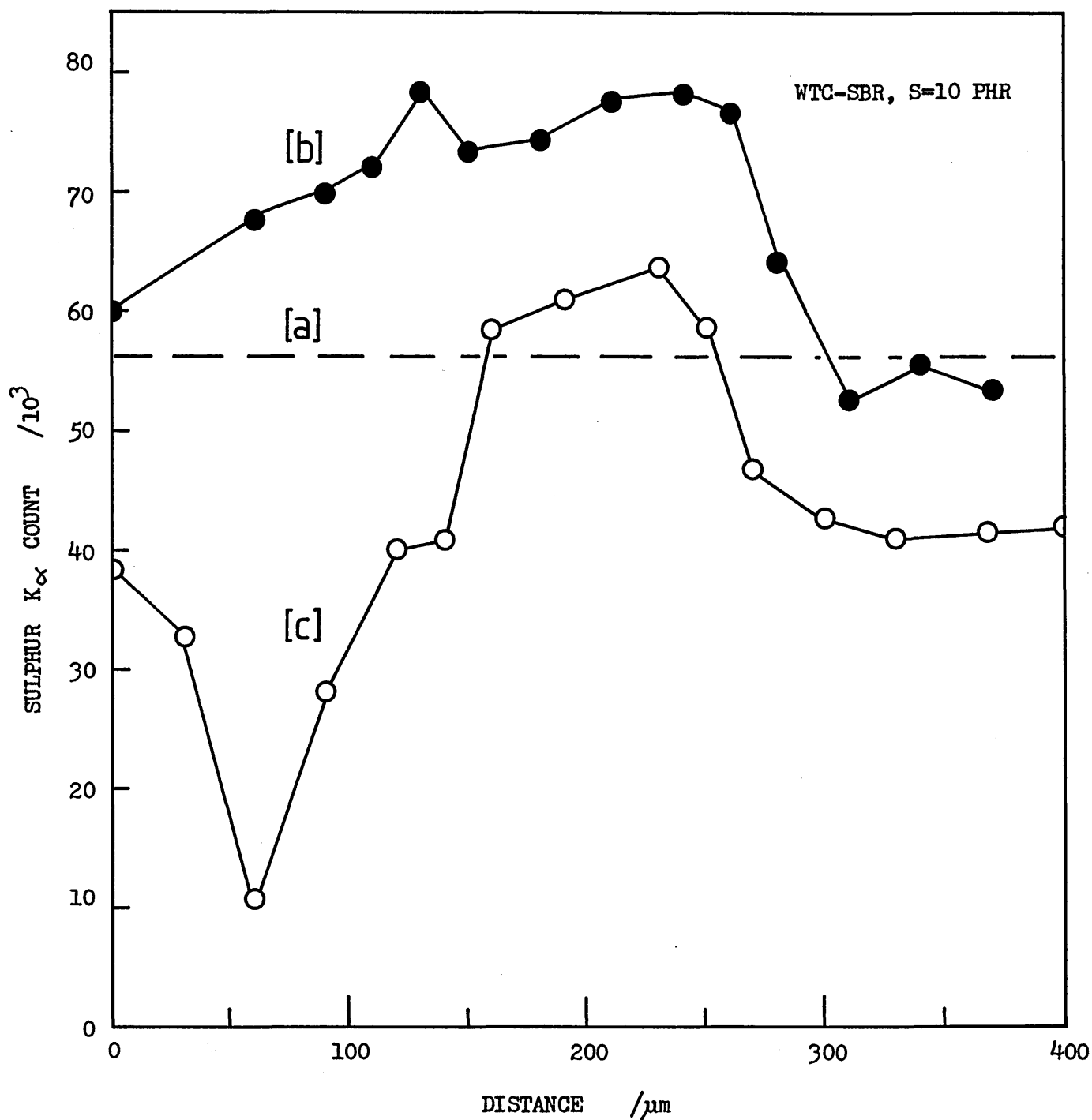


FIGURE 6.12 Variation of integrated sulphur K peak count obtained by point analysis as a function of distance across a crumb particle for WTC - SBR, S = 10 phr. (a) $\phi_{RR} = 0$; (b) $\phi_{RR} = 20$; (c) $\phi_{RR} = 50$.

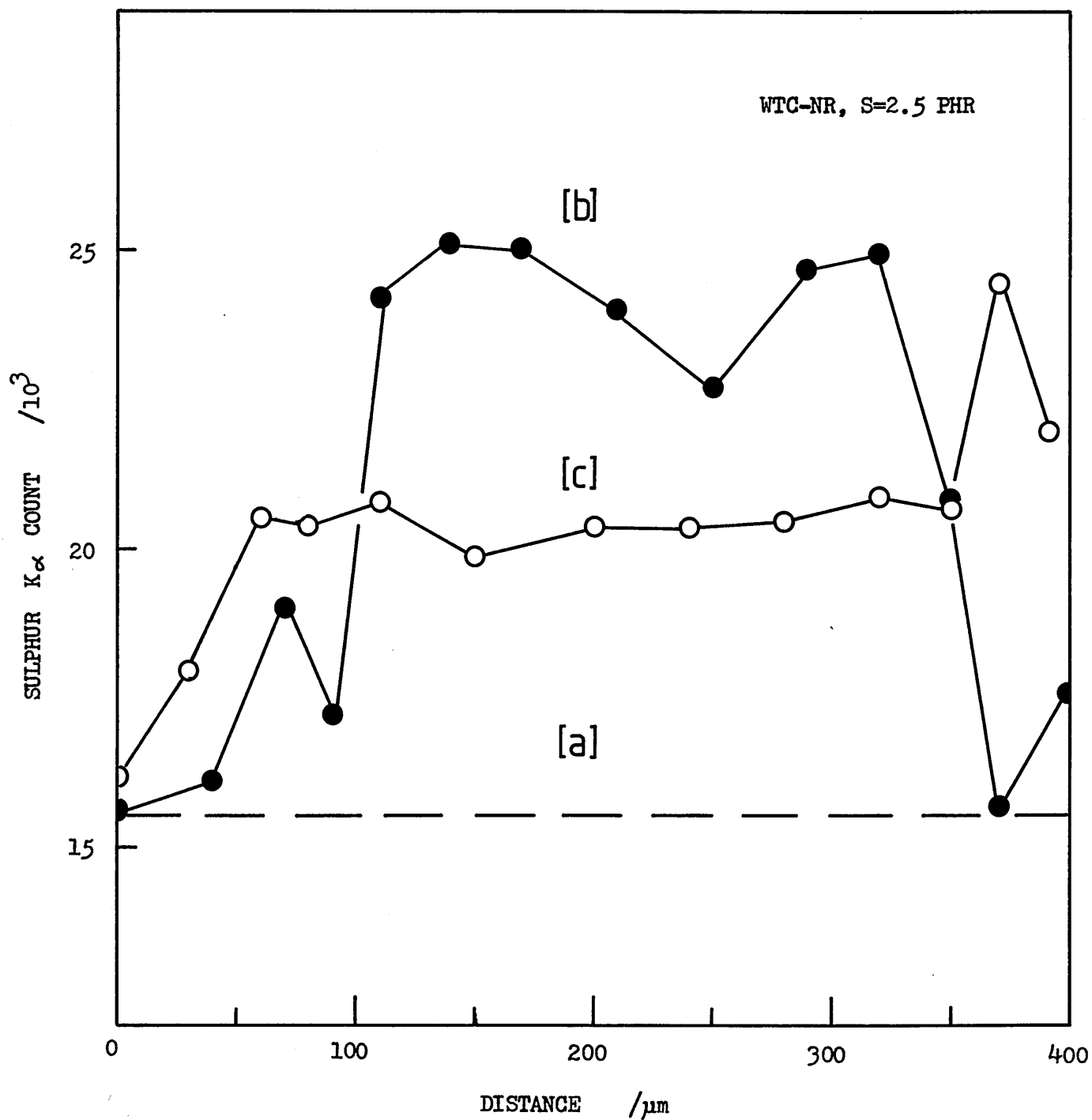


FIGURE 6.13 Variation of integrated sulphur K α count obtained by point analysis as a function of distance across a crumb particle for WTC - NR, S = 2.5 phr. (a) $\phi_{RR} = 0$; (b) $\phi_{RR} = 20$; (c) $\phi_{RR} = 50$.

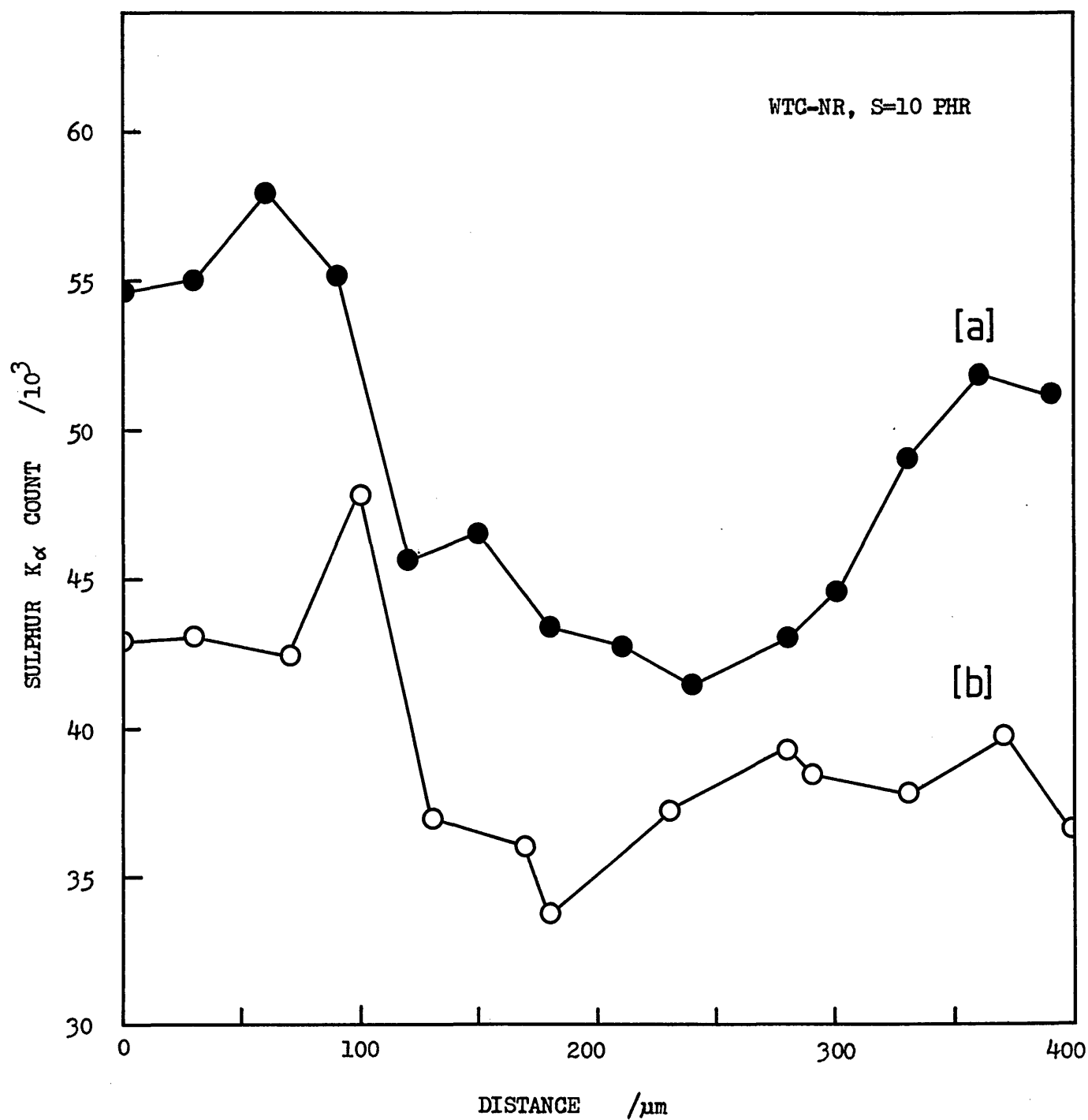


FIGURE 6.14 Variation of integrated sulphur K peak count obtained by point analysis as a function of distance across a crumb particle for WTC - NR, S = 10 phr. (a) $\phi_{RR} = 20$; (b) $\phi_{RR} = 50$.

However, due to the chemical similarity of the specimens, it is felt that the ZAF correction will be small. Other factors, such as topographical effects, local surface tilt, the size and location of individual rubber crumb and the capture volume effect may have a more serious consequence on the analysis. Unfortunately, these effects cannot be easily eliminated and that the exact extend of the effects cannot be easily quantified. Despite this uncertainty, the results are useful in identifying the mechanisms underlying the curative redistribution behaviour.

Table 6.1 presents a summary of the semiquantitative results of the point-to-point analysis. Together with qualitative evidence obtained from the X-ray sulphur maps and line scans, these results clearly indicated that for the SBR based system, sulphur has migrated from the matrix into the vulcanized rubber crumb particles. This behaviour is in agreement with Grebenkina et al (160), whose system also consisted of an unvulcanized and a cured phases. However, the direction of sulphur migration is in contradiction with the prediction by the distribution parameter technique (Gardiner). (The rubber crumb derived from whole tyres will contain about 60:40 of SBR:NR, the solubility of sulphur in SBR being greater than in NR). Gardiner calculated a distribution parameter of 1.18 for the SBR/NR pair (distribution parameter = solubility of ingredient in A / solubility of that ingredient in B), indicating that due to higher solubility in SBR, sulphur will diffuse into SBR. In order to reconcile this apparent contradiction, the factors that may have affected the sulphur migration must be considered.

Firstly, the solubility parameters obtained by Gardiner were those for unvulcanized rubbers. These may not necessary be the same for vulcanized rubbers. The lower apparent activation energy of combination of sulphur and crosslinked rubbers, as stated by Grebenkina et al, indicates that it is more likely that the solubilities of sulphur in crosslinked rubbers are higher than their uncrosslinked counterparts. Hence, the distribution parameter technique, as used by Gardiner (190, 191) and Guillaumond (192) may not be applicable in the vulcanized - unvulcanized rubber systems.

The initial free sulphur concentration in the SBR matrix is much higher than that in the vulcanized rubber crumb (although the crumb should contain 2-3 phrs of bound sulphur from previous vulcanization process).

TABLE 6.1 Maximum sulphur K_α-line integrated counts comparison

WTC-SBR	ϕ_{RR} (phr)	0	20	50
<u>S = 1</u>	Max. count Ratio	8,000 1	29,000 3.6	16,000 2.0
<u>S = 2</u>	Max. count Ratio	25,000 1	62,000 2.5	39,500 1.6
<u>S = 5</u>	Max. count Ratio	33,500 1	69,000 2.1	57,000 1.7
<u>S = 10</u>	Max. count Ratio	56,000 1	78,000 1.4	63,000 1.1
<u>WTC-SBR</u> <u>S = 2.5</u>	Max. count Ratio	15,600 1	25,000 1.6	20,700 1.3

NOTE:

Maximum count = sulphur K_α-line integrated counts at the peaks of the line scans obtained by point-to-point analysis.

$$\text{Ratio} = \frac{\text{Maximum count for } \phi_{RR} = 20 \text{ or } \phi_{RR} = 50 \text{ phr.}}{\text{Maximum count for } \phi_{RR} = 0 \text{ phr.}}$$

Hence, sulphur migration from the SBR matrix into the crumb occurs in order to equilibrate the free sulphur concentration difference.

NR based material system appeared to exhibit a smaller degree of sulphur migration, as evident from the X-ray sulphur maps and line scans, and from the point-to-point analysis shown in Figures 6.13 and 6.14. The reason for this observation may lie upon the higher unsaturation of NR and the relative fast cure rate of NR compounds. Gardiner and Guillaumond have noted that molecular unsaturation and polarity (NR is more polar, and hence more active double bond unsaturations than SBR's) played a role in determining the direction of curative migration. The relatively higher rate of vulcanization of NR compounds meant that the free sulphur content in the NR matrix decreases rapidly, thus reduces quickly the driving force (the difference in free sulphur concentrations) which would otherwise causing sulphur migration into the crumb particles. This effect of relative rate of vulcanizing on curative migration was also observed by Baranwal and Son (195). The net effect is therefore, less sulphur migration in NR-recycled rubber composites.

Referring to Table 6.1, and from Figure 6.15 it can be seen that the concentration of sulphur in the crumb decreases with increasing rubber crumb loading. This is as expected, as there are $1\frac{1}{2}$ times more crumb in the $\phi_{RR}=50$ phr mix than that in the $\phi_{RR}=20$ phr mix and the amount of sulphur formulated into the matrix mix is fixed. This observation is also true for different levels of sulphur, although at higher sulphur levels, the differences in sulphur concentrations become relatively small. This smaller sulphur concentration differences could have been due to the excessive amount of sulphur (over the saturation level) being compounded into the mixes. The excessive sulphur thus exists as free sulphur in the mix and encourages migration into the crumb. Evidence of the existence of excessive free sulphur can be seen as sulphur blooms in the micrographs of high sulphur loaded mixes (mixes with 5 and 10 phr of sulphur). In some cases, sulphur bloom can be seen on cut particle surfaces.

Although strict quantitative comparisons may not be made (due to slightly difference in operating conditions for each run), the general trend of increasing intensity counts with higher sulphur loadings can be observed, as would be expected. This is shown graphically for the base compounds in Figure 6.16. Ratios of these intensity counts to that

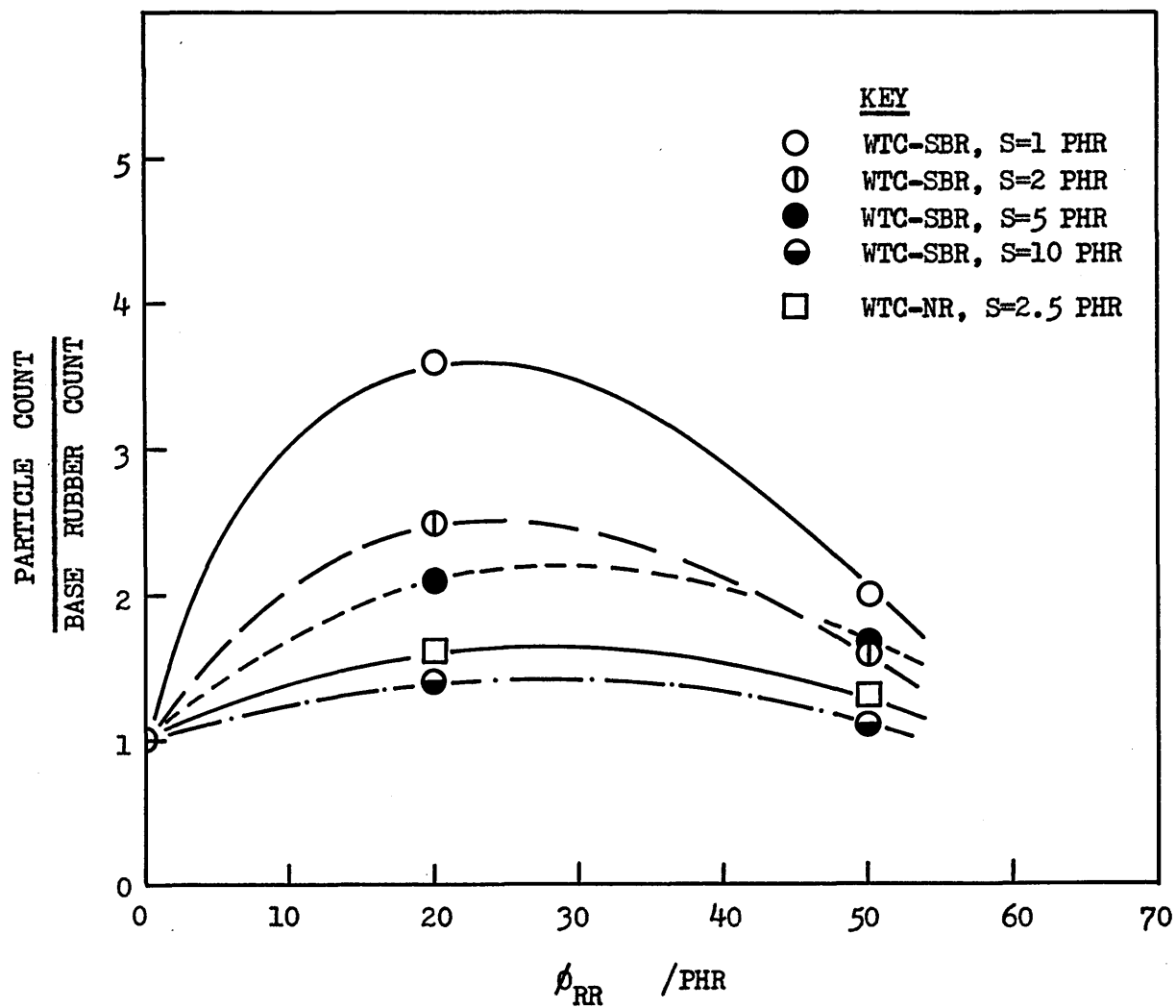


FIGURE 6.15 Ratios of sulphur K_{α} integrated counts in the particle and that in the base rubber as a function of recycled rubber crumb loadings.

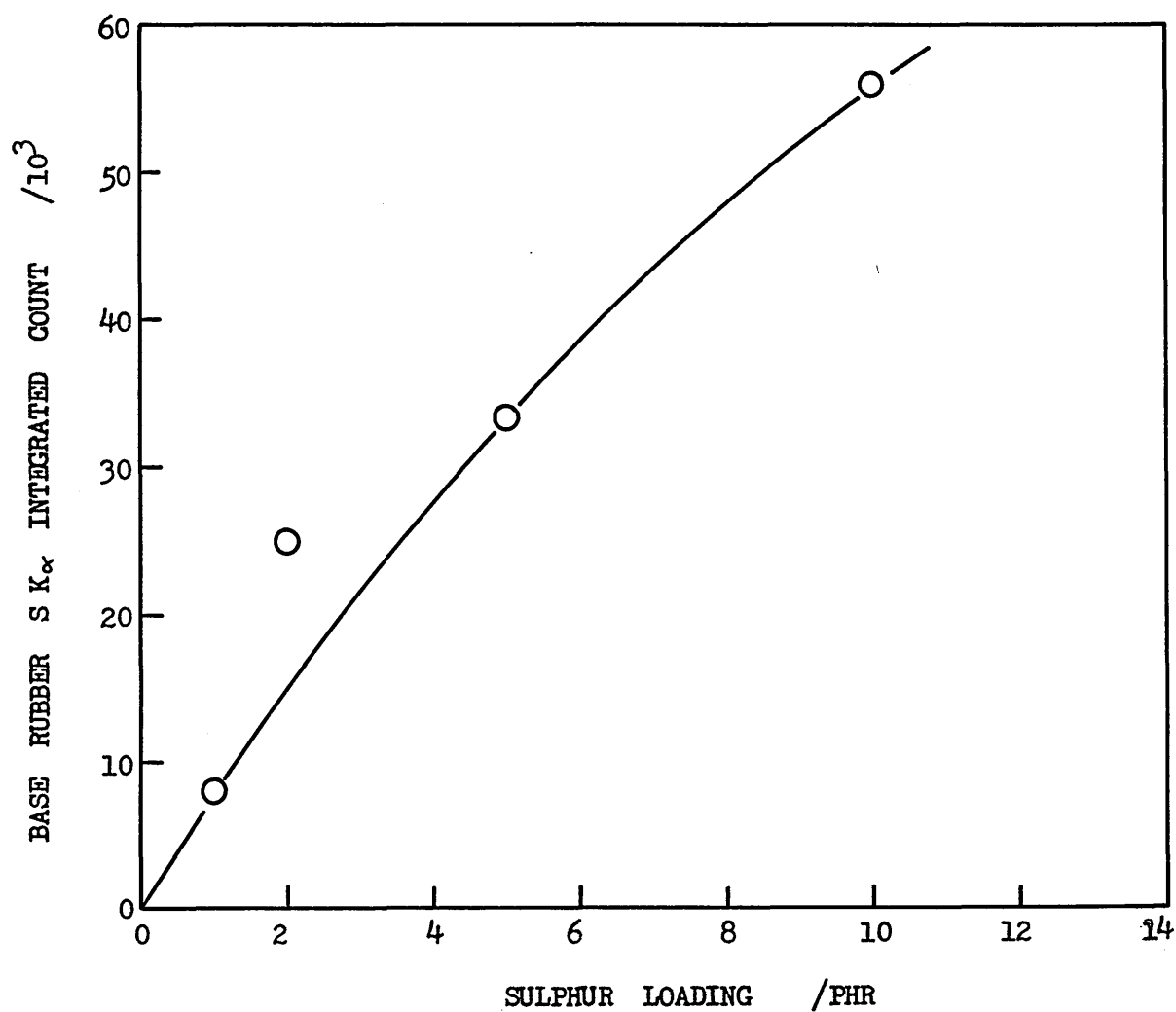


FIGURE 6.16 Graph of Sulphur K α Integrated Counts in the Base Rubbers (i.e. with $\phi_{RR} = 0$) as a function of Sulphur Loadings in the SBR based Compounds.

of the corresponding gum mixes (with $\phi_{RR}=0$) can be calculated to allow comparison be made between runs (hence with different sulphur loadings). Looking down the columns of Table 6.1 i.e. with increasing sulphur loading, and also presented in Figure 6.16, the ratios show a general decreasing tendency, indicating that as the sulphur loading is increased, the sulphur concentrations in the crumb approach that of the gum mixes. This suggests that the final sulphur concentrations in different components of a rubber-recycled rubber crumb material systems depends to a certain extent to the initial concentrations of sulphur in the matrix mixes.

Referring to the X-ray line scans and scan lines plotted from the semiquantitative point-to-point analysis, the interfacial curative depleted zones (as proposed by Gardiner (190, 191)) do not appear conclusively, although some depressions in the lines can be seen at some matrix-crumb particle interfaces. Cross examinations with the corresponding micrographs and X-ray sulphur maps attribute these depressions to the topographical effects (the unevenness of the matrix-particle interface). Micrograph of $\phi_{RR}=20$, $S=1$, and X-ray maps of $\phi_{RR}=50$, $S=1$ and $\phi_{RR}=50$, $S=2$, are some of the examples.

It can also be seen from these line scans that, for the most part, the sulphur concentration remained approximately constant across the particle, and there was a rapid change in sulphur concentration at the matrix-particle interface. The sulphur concentration of the matrix of systems containing rubber crumb was less than that for unfilled gum mixes. It is therefore, not surprising to expect a general lowering of physical properties when vulcanized rubber crumb is introduced into a rubber mix.

6.5 Conclusion

The SEM study has provided qualitative and semiquantitative evidence for the uneven spatial distribution of sulphur in the SBR1500 and NR based material systems. This spatial distribution of sulphur has resulted from the redistribution of free sulphur incorporated into the base rubber mix, the free sulphur tends to migrate from the mix into the rubber crumb particles. The extend of sulphur redistribution has been found, in terms of compounding variables, to depend on a) the amount of sulphur incorporated into the base rubber mix; b) the amount of recycled rubber crumb present in the compound and c) the nature of the base rubber.

Time and temperature of vulcanization, which may have affected the redistribution of sulphur, have not been examined.

Although a detailed discussion of the mechanisms governing the diffusion and in particular the redistribution, of free sulphur cannot be engaged upon, due primarily to the lack of appropriate data and understanding in the complex sulphur vulcanization reactions in these complex material systems, the SEM study and that of the other workers have indicated a number of important factors. These are

- a) the relative solubility of sulphur in the rubbers;
- b) the initial amount of sulphur incorporated into the base rubber mix;
- c) the degree of unsaturation in the matrix and crumb;
- d) the degree of crosslinking and its effect on the activation energy of sulphur crosslinking reactions;
- e) the relative rate of sulphur crosslinking of the rubbers;
- and f) the time and temperature of mixing, storing and vulcanizing.

There is no strong evidence to show the existence of a sulphur depleted region at the matrix-crumb interface in either the WTC-SBR or WTC-NR composites. The apparent absence of this sulphur depleted zone may be taken as an indication for existence of some form of bonding between the matrix and crumb particles. If this is correct, then it may be used to explain the enhancement of both the modulus and tensile strength of WTC-SBR composites with increasing sulphur levels and rubber crumb loadings (the crumb is estimated to have higher modulus and strength than the SBR matrix).

7.1 General Considerations

Economic and cost data and information on rubber recycling processes are usually disguised in most literature and review articles. The data and information are often expressed in ambiguous terms, and often incomplete, thus limiting their usefulness. Typically, a wide range of values of a variable will be given, the range is usually so wide that it covers almost every possibility.

It is extremely difficult to obtain cost data and information, with sufficient reliability and accuracy, directly from companies involved in rubber recycling. Industrial secrecy and confidentiality plays an important role here. Attempts to obtain data from existing operations are hampered by the lack of enthusiasm of an ailing industry. The piece meal nature of the acquisition of capital equipment and the numerous modifications and improvements made to the initial equipment hinder the determination of a reliable cost figure. When the operation is a subsidiary or part of a company, it is likely that the costs are incorporated in the costs of the whole company, and hence prevent the costs of the rubber recycling operation from being clearly separated.

The existing operators of the more modern technology such as the cryogenic grinding processes have encountered some difficulties, and are known to have stopped operating. These companies are particularly sensitive to enquiries regarding cost data and information. The supply of cryogenic grinding equipment is either controlled by or affiliated to the two main liquid gas suppliers, each eyeing cryogenic rubber grinding with considerable enthusiasm because of the potentially high volume of consumption of liquid nitrogen by these processes. However, collection of cost data becomes extremely delicate as each liquid gas company tries to dominate the supply of liquid nitrogen to the cryogenic rubber grinding industry and show some lack of willingness to provide operating and other cost data.

In view of the above mentioned difficulties, sufficient cost data for only a particular cryogenic grinding process was obtained. Cost data collected for other processes was either incomplete for any useful analysis, or ambiguous.

7.2 Development Costs

Development costs are excluded in the quantitative cost analysis in the later section for reasons discussed in the following paragraphs:

Development cost as applied to rubber recycling processes, consists of costs for initial theoretical development stages, the laboratory scale operations, pilot plant operations and scale-up pilot plants. One major aim of the development stage is to generate sufficient data, both technical and economic, to determine the optimum size and operating conditions, and to justify the progress into the production scale plant.

In cryogenic rubber grinding, the plant R & D is largely carried out or supported by the two major liquid gas companies (An Products and BOC) for reasons discussed earlier. The rubber recyclers tend to be plant buyers, commissioners and modifiers.

Development cost is almost always sunk in the capital equipment costs in the case of a development bought from outside the company. The payment of licence fees, royalties may be considered as a form of development cost. In the case of the project developed within the company, development cost is often offset by the project of other parts of the company, as it is often written off as part of the fixed costs of the whole company.

It has not been possible to isolate development cost from the limited published data in view of the above mentioned complexities. Licence fee may appear to offer certain indication of the magnitude of development cost. However, the licence fee for a particular process charged to each individual company can vary quite substantially. This will depend on the existence of any other business connections between the twocompanies, the size of the business, and the nature and geographical location of the purchasing company. Unless the licence fee is for the purchase of a mobile turn-key plant which is guaranteed to work at optimum conditions, extra costs of setting up the plant and obtaining the optimum operating conditions may constitute a substantial cost in addition to the licence fee. Given that all the processes considered in this study are not mobile, licence fee becomes meaningless as development cost indicator, and are excluded in the economic analysis. The final results from the economic analysis, therefore must be adjusted for any estimated development cost of a particular company and this can only

have an adverse effect on the economic feasibility of the project.

7.3 Process Economics : Cost Factors Involved

This section presents qualitative treatments of the cost factors involved in a rubber recycling processes. A wider approach is taken in the discussion, which gives a general description of the cost factor as applicable to rubber recycling, and then follows by a more specific detail of the factor for a cryogenic scrap rubber tyre grinding process. Quantitative analyses are presented in the next section, 7.4.

A. Capital Costs

Total capital costs consist of capital equipment and installation costs, working capital and cost of land and building. The capital costs are actually spread over periods of more than one year, but due to the uncertainty in the actual period of the spread, and to simplify calculations, these costs are assumed to be incurred at the beginning of the commission of the project. If capital cost is incurred before the commission of the project, there will be an understimation of the capital cost and an overestimation of NPV.

a) Capital equipment and installation costs are the costs of production machinery such as the digesting chamber, reclaimator, the screw feeder, the freezing chamber, the mills and grinders etc which are necessary for the manufacturing of the product (recycled rubber in this case), and the costs of the foundations and support structures for the machinery. The cost of installation is also included in the capital equipment and installation costs.

It is extremely difficult to estimate or obtain sufficiently accurate indication of the capital costs of older operations. The survey of European and American rubber recycling facilities, presented in Appendix A, indicated a capital equipment cost range of between £500,000 and £1.5 million. However, these are not new plants, and hence the capital cost data would probably be derived from out of date data. The piecemeal additions to the older plants for the purposes of improvement, modification and/or expansion since the installation of the original equipment, created further complications. While for the other plants in the UK, mostly employing cryogenic grinding technology, secrecy and protectionism prevailed coupled with a slack market for the product and fierce competition from the tyre retreading sector (which produces finely

ground rubber as a by-product), making collection of cost data of any kind an almost impossible task. Despite the lack of enthusiasm, capital equipment and installation cost for a 1 to 3 tonne per hour throughput cryogenic grinding facility have been estimated to range from £500,000 and £1 million (see Appendix G).

Capital equipment and installation costs also present a different set of problems in that for a particular process, it is possible to combine the various bits of capital equipment together in a number of combinations. Each combination would differ in input and output capacity, nature of output, efficiency in processing and hence would be expected to produce different potential profitability. Taking cryogenic grinding as an example, the main items of capital equipment are the tyre shredder, freezing chamber, grinder and the screening/sifting system. Tyre shredder is a fairly standard piece of equipment, hence a large variation in performance and cost will not be expected. The same may be expected of the screening/sifting system. However, the selection of freezing chamber and grinder is of great importance. Various types and designs of freezing chambers exist. As will be seen in the later section, cryogenic medium cost is the most important operating cost in the cryogenic grinding process, and the selection of the most efficient design of freezing chamber may make the difference between the whole process being economically feasible or otherwise. Taking the freezing chamber as a specific illustration, the rotary type is claimed to be more technically advantageous compared with a belt-driven type. Although lack of technical information hampered further analysis, however, plain physical operation of the two designs of freezing tunnels may serve as an indication: due to the poor heat conductivity of rubbers, physically turning the rubber pieces as in the rotary tunnel can be expected to facilitate better mixing of cryogenic medium and the rubber, hence improving the freezing efficiency. The selection of grinder/mill is also of significant importance.

Economic analysis of a process is often dictated by the availability of technical and cost data. As mentioned earlier, relatively complete data for a cryogenic grinding process only was available. The following fixed capital cost discussion will be confined to this cryogenic grinding process.

The process under consideration was jointly developed by Newell Dunford (ND), KEK and BOC. It consists essentially of two grinding stages. The first stage is the primary grinding using the ND system yields a coarse crumb as product. Systems designed with 1, 2 and 3 tonne per hour (of scrap tyre input) (TPH) capacity can be used, and associated with them their capital and operating costs. The stage two secondary grinding is carried out with the KEK-BOC system. The largest of the KEK-BOC system has a maximum capacity of 0.8 tonnes of input per hour, therefore it is necessary to install more than one such system for primary grinding systems with higher capacities, resulting in four possible combinations (refer Figure 7.1):

Plant Combination I	: 1 TPH System + 1	2-H Mill System;
Plant Combination II	: 2 TPH System + 2	2-H Mills System;
Plant Combination III	: 3 TPH System + 3	2-H Mills System; and
Plant Combination IV	: 3 TPH System + 2	2-H Mills System.

It is possible to form other combinations by using secondary grinding systems developed by other companies such as that used by the Trellfax AB (Sweden) based on Condux Mills (German), but all later analyses will be restricted to the above four plant combinations due, primarily, to the relative completeness of cost data obtained for the four combinations. In combinations I, II and III, the secondary grinding facility will be underemployed, while for combination IV, the primary grinding plant will be underemployed. The capital equipment and installation cost data is contained in Appendix G.

b) Working Capital can be considered as the amount of money required for raw material, semi-finished and finished goods stocks, to maintain creditors and debtors, to ensure a smooth flow of production and sales, and to cater for any emergency need for cash. Various techniques and methods exist for estimating working capital (137, 138). In view of the comparatively simple rubber recycling processes, work-in-progress has been assumed to be negligible and the working capital is taken as two months supply of raw material i.e. scrap tyres and rubber, and two months stock of finished goods i.e. reclaimed rubber or rubber crumb. Treatment of debtors, trade creditors and cash depends on the individual policies of companies and it has been assumed here that trade creditors and bank overdraft completely offset debtors. However, this estimate is likely to understate working capital by some amount in practice. (The

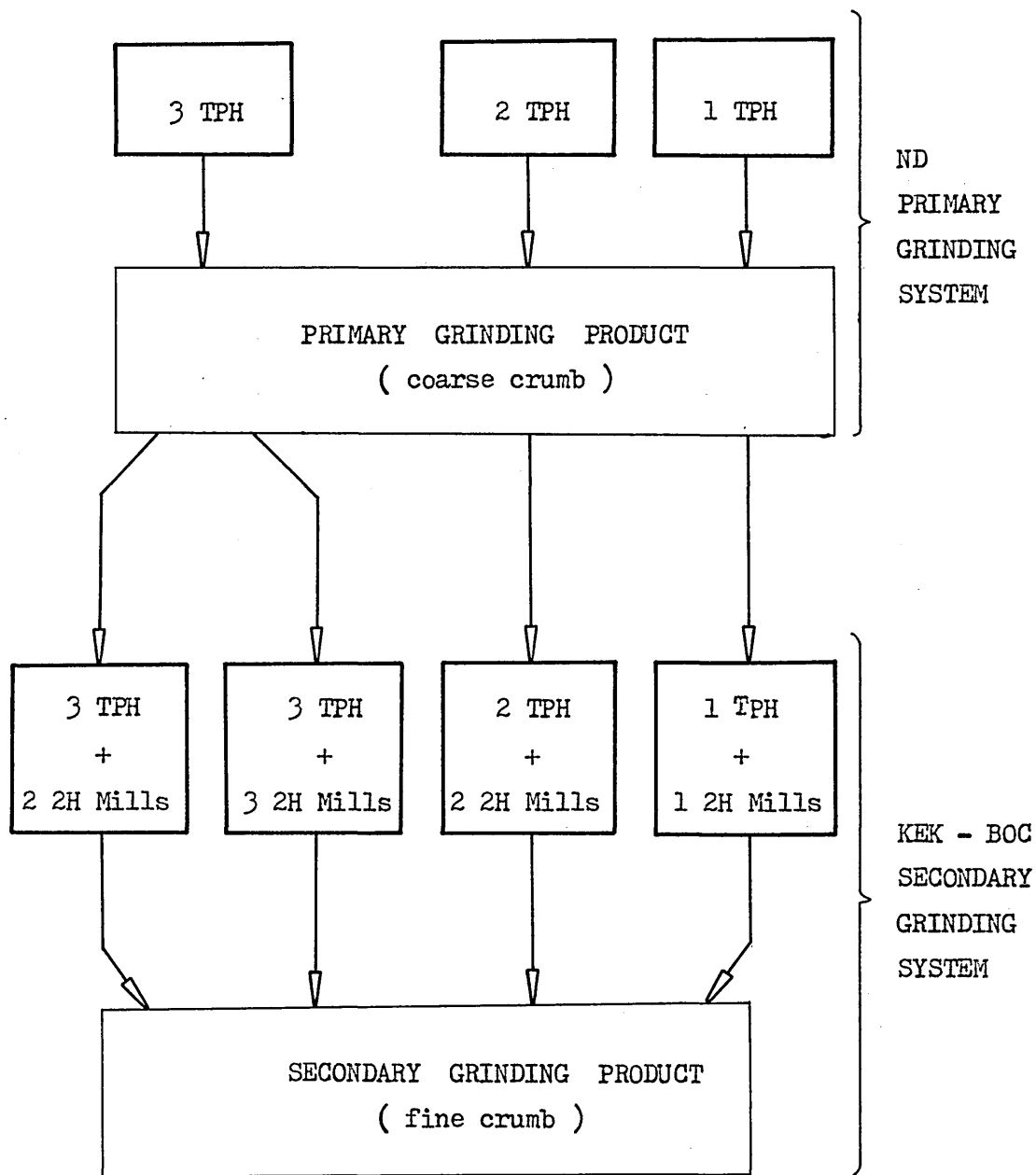


FIGURE 7.1 Capital Equipment Combination Diagram for ND, KEK-BOC Process

stock of liquid nitrogen is excluded from the working capital. If 95 operating hours of liquid nitrogen stock is carried, the stock will last for 3 - 4 working days, which means the tanks must be filled every 3 - 4 days. If a credit term of 5 days is granted from the liquid nitrogen supplier, payment for the first batch of liquid nitrogen is due 5 days after delivery, by then the second batch has to be delivered. And being a substantial customer, the credit term is more likely to be more than 5 days. Therefore, effectively, the stock of liquid nitrogen is carried by the liquid nitrogen supplier.)

c) Land and Building Costs vary greatly from one geographical region to another. The cost of land and building in the South-East region would quite definitely cost considerably more than perhaps in the North-West. In most cases, companies which may be interested in large scale rubber recycling may already own suitable land and buildings. The Regional Industrial Development Incentive Scheme provides land and building at very favourable terms, thus adding more difficulties in arriving at a fair estimate of land and building costs. In view of these complications and the likelihood of arriving at an unrealistic estimate, land and building costs are left out of the total capital costs and are assumed to be rented and included in the estimate of the fixed costs per annum. Like working capital, land and building costs are recovered at the end of the project life, thus also minimising the effect of excluding it in the analysis.

B. Operating Costs

Operating costs are customarily divided into variable costs and fixed costs. The problem of semi-variable costs is dealt with when discussing particular items of cost.

a) Variable Cost the direct material in rubber recycling processes is, obviously, scrap rubber. As pointed out previously, the most likely and most abundant source of scrap rubber is scrap rubber tyres. The actual cost of the scrap tyre itself is insignificant, in fact it was reported (121) that in certain parts of UK, scrap tyres have a negative value, i.e. payment was received to take the scrap tyre away. The cost of scrap tyres can therefore taken as the cost of collecting and transporting them to the processing centre. In the era of high transport costs, coupled with the bulky nature of the scrap tyres, the net cost of scrap tyres represent about 10% of total variable costs for a cryogenic grinding

process (see Appendix G). Currently, the supply of scrap tyres is well able to satisfy the demand of the present rubber recycling operations with cheap (sometimes almost free) raw material. However this situation may change if and when there are more rubber recycling plants in operation (a 3 tonne per hour plant in full operation requires about 2.5 million scrap passenger car tyres each year, and the total number of scrap tyres generated each year is estimated at about 20 million, one third of which is estimated to have been recycled through retreading, therefore theoretically, a maximum five such plant can be sustained. However, in reality due to the wide distribution of the scrap tyres, three plants around densely populated regions such as London, Birmingham and Manchester, is possibly the maximum number.) More effort would be required to collect the tyres if more than three plants because transport costs can only be kept to a reasonable level within large population centres. Consequently the cost of raw material for rubber recycling industry is not as favourable as it may seem.

The other direct materials are those needed for the production of the recycled rubber. Chemical reclaiming agents for the conventional chemical reclaiming processes, and liquid nitrogen for the cryogenic grinding processes. A figure of 25% of the total variable cost was quoted for a chemical reclaiming process (45) and liquid nitrogen cost represents about 70% of the total variable cost for a cryogenic grinding process (see Appendix G). All processes require power to operate. While the chemical reclaim process, a high energy user, required about 25% of the total variable cost as electrical power, the cryogenic grinding process consumes less than 10% of the total variable cost as power.

Other items of the variable costs are spares and maintenance, waste disposal, and wages and salaries. Waste disposal cost is the cost of disposing of the bead wire, steel belt, fabric flock and other foreign materials such as sand, grit and fibre-glass. It is envisaged that the scrap steel belt separated may be sold as scrap steel, thus bringing in additional revenue. The scrap steel sales depend mainly on the purity of the steel and the degree of compactness the steel belt can be compressed. The quality of the steel does not pose any problem -- it is high tensile steel coated with brass (to assist rubber-to-metal bonding). In the case of conventional reclaiming process high levels of manning and skilled labour are necessary, hence a high wages and salaries of about 28% of the total variable cost (45). In contrast, the automated

nature of the cryogenic grinding process permits it to employ less and relatively unskilled labour. Thus reducing the wages and salaries costs as a proportion of total variable cost.

b) Fixed Costs the main items of the fixed costs are the cost of administration, rent, rates and insurance on land and building, sales and distribution, and other miscellaneous fixed costs. The cryogenic grinding processes would require an additional item of fixed cost, the liquid nitrogen tank rental. The fixed liquid nitrogen tank rental is in addition to the cost of liquid nitrogen consumed, and its magnitude depends on the size and the number of tanks installed. The administration cost for ND, KEK-BOC's cryogenic grinding process (see Appendix G) includes both the technical and administrative supports for the operation. For a three tonne (input) per hour plant, in full operation, it is assumed that a team of a plant/production manager and two laboratory technicians with the appropriate laboratory facility would be required to provide the necessary technical support. Administrative support would be provided by a managing director/general manager, and a team of two secretaries and two accounting staff. Sales and distribution would be provided by a team of two sales representatives. Other miscellaneous costs includes warehousing, laboratory expenses and general office requirements. The fixed costs for such a plant are likely to represent about 15% of the total operating costs.

The fixed costs of the plants studied here are not expected to vary very much with the design capacity. The technical and administrative supports, sales and distribution supports and the land and building requirement are expected and assumed to be the same for a 2 and 3 tonne per hour plant. Hence, smaller output plants will have a higher fixed costs per unit output. Consequently, the smaller plants are less attractive.

G. Pricing of Recycled Rubber

Figure 2.7 shows the price movements for the 30 mesh and 40 mesh tread rubber crumb (122). The prices followed a steady increase through 1978 and a more rapid increase thereafter. Given the declining consumption pattern of reclaimed rubber (see earlier Chapter on supply, consumption and stock of rubbers) over the period of late 1970's, it is doubtful if the prices of rubber crumb will stand as shown in Figure 2.7. Evidence of a price collapse was confirmed (141). In 1980, 30 mesh tread crumb was priced at £180 per tonne, in April 1981, the price on open market

for tyre tread buffings was £65 per tonne. By December 1981, the price for 30 mesh remained at about £180, and that for 40 mesh crumb was about £220 per tonne. The data presented in Figure 2.7 are average values for the particular year, hence they failed to reflect the price movement within the year. The price movement within a year can be quite considerable. Such fluctuation and uncertainties make it extremely difficult to establish the price for rubber crumb with some degree of confidence.

With the closure of one of the two recycled rubber manufacturers in the UK, the price of recycled rubber may be expected to stabilise. For the monopolistic supply situation may be true for reclaimed rubber (this is not quite true as reclaimed rubber is also imported), rubber crumb, especially the larger mesh crumb (30 mesh or larger) has alternative sources (eg. coarse crumb is produced as a by-product of a tyre retreading operation). These alternative sources of crumb supply has prevented a more stable rubber crumb price.

"Soft" prices for rubber crumb are expected to prevail for the near future, as the economic health of the rubber industry in general is in the decline, and one of the major uses of rubber crumb, carpet underlay, is facing serious competition from other materials such as SBR rubber foam and polyurethane foam (146). The reluctance of rubber product manufacturers to use more than the minimal amount of recycled rubber in the products, does not help matters. The US Department of Energy's proposal that a minimum of 5% of recycled rubber should be incorporated in all rubber products produced in USA (127) gives an encouraging sign for a more stable recycled rubber prices. However, in this country such enforced usage is unlikely because the existing users may resist the introduction of such legislation. Further more, as many rubber products, especially the extruded products and tyres, are already using about 5% of recycled rubber to assist processing, the impact of a 5% minimum recycled rubber usage in rubber products would be small.

Another problem of pricing the recycled rubber concerns the fixing of a single price for the output of a process. For the conventional reclaiming process such as the reclaimator process, the output consists of reclaimed rubber of various grades, as well as rubber crumb. The method adopted to overcome this difficulty is a composite price. Taking

the ND, KEK-BOC cryogenic grinding process as an example, the output from the process consists typically of about 50% of 40 mesh crumb, 20% of 30 mesh crumb and 30% of coarse crumb (145). If the prices for 40 mesh, 30 mesh and coarse crumb are £220, £180 and £60 per tonne respectively (Dec. 1981), the composite price for the output is calculated as:

$$\begin{aligned}\text{Composite Price of Output} &= (£220 \times 0.5) + (£180 \times 0.2) + (£60 \times 0.3) \text{ p.t.} \\ &= (£110 + £36 + £18) \text{ per tonne} \\ &= £164 \text{ per tonne}\end{aligned}$$

The composite price can only hold true if all the output is sold in their fixed proportions over time.

In view of the difficulties and uncertainties in pricing, a range of composite prices of between £160 and £180 per tonne of rubber crumb output with about 50% of 40 mesh, 20% of 30 mesh and 30% of coarse crumb will be used for the quantitative analysis in the later section.

D. Other Costs

a) Tax: corporation tax is paid on taxable income (after deduction of capital allowances). There is a delay of at least nine months before tax on the taxable income is actually required to be paid (all companies established after April 1965 pay nine months after account year end). In the later economic analysis, a 12 months delay will be assumed to simplify calculations. Cash flows are assumed to occur at the end of each year because this is the basis on which Present Value tables are prepared. The current rate of corporation tax of 52% is used.

A rubber recycling facility can exist as an independent company, or the recycling operation may be part of an existing company with other operations such as tyre manufacturing (see Figure 2.2). In the former case, taxes may be deferred until the company is profit making. With a dependent operation, if the rubber recycling operation is not profitable, capital costs of the operation may be offset against taxable income generated by other operations of the company. Effectively, part of the capital costs of the operation will still be recovered and the company as a whole pays less tax. An analysis will be made of both these extreme cases.

b) Inflation: Inflation will have an adverse effect on the costs. Inflationary increases in costs must be counter-balanced by a proportional increase in the price of output, which would otherwise result in a project becoming economically less attractive.

The effect of inflation is complex, and requires thorough knowledge of factors governing inflation. To overcome this additional complexity, the interest rate assumed or generated will be assumed to be a real rate of return and that cost and revenue estimates are in terms of real values.

c) Interest Charges: In the Discount Cash Flow (DCF) investment appraisal techniques, an investment must generate an internal rate of return (IRR) which is equal to or greater than a chosen required rate of return. An IRR that is equal to or greater than the required rate of return will ensure that the cash flows generated will be sufficient to pay the interest charges on the investment loan and repay the loan principal.

A company may set its own rate according to its internal requirements but the appropriate discount rate will vary from company to company. Bank lending rates are perhaps one of the most objective indicators of the magnitude of the rate a company might use. Bank lending rates applied vary from industry to industry, and company to company depending on the industry, the risk involved, and the assets and management of the company. In a high risk venture like the rubber recycling operation, a non-prime lending rate will apply, which is several percentage points higher than the usual interest rate. As a guide to the magnitude of the interest rate, we may consider the interest rate payable on a Loan Stock in the Stock Market for a related industry. Since a cryogenic tyre grinding plant will be a major consumer of liquid nitrogen, we may base our estimation on the interest rate of Loan Stock issued by a liquid gas manufacturer. A Loan Stock of 12% interest rate was issued by BOC Ltd in December 1982. Taking into considerations the diverse industrial interest and the established reputation of BOC, and with the addition of a premium to reflect the risky nature of this type of investment, a 20% rate of interest (approximately 10% net of tax) would be a reasonable estimate.

7.4 Process Economics : Economic Analysis

The economic analysis performed in this section were carried out using cost data for a cryogenic grinding process compiled with the kind assistance of several industrial contacts (121, 125, 140). These cost data were presented in Appendix G.

A. Analytical Techniques Employed

The economic analysis performed are:

- a) Net Present Value (NPV);
- b) Internal Rate of Return (IRR);
- c) Breakeven and Sensitivity Analysis; and
- d) Investment Simulation.

The NPV and IRR techniques are used in favour of other methods of investment appraisal methods such as Payback Period (PBP) and Accounting Return on Investment (AccRoI) because both NPV and IRR use cash flows, recognise the time value of money, and both consider the whole of the project life. AccRoI uses annual profits, which may be defined in a number of ways, instead of cash flow, and it does not recognise the time value of money, PBP can be made to recognise time value of money by using a Discounted PBP. However, PBP does not consider the whole life of the project. (For further discussion, see for example references 137, 138, 185, 186)

a) Net Present Value (NPV) is one of the two major Discounted Cash Flow (DCF) measures of economic value of a proposed investment -- the other being IRR. The NPV of an investment is equal to the difference between the sum of the present value of the forecasted cash flows of the project, and the present value of the investment in capital assets and working capital. Present values of future cash flows are derived by the method known as "discounting" which is the reverse of compounding (as in compound interest calculation). With the selection of an appropriate discount rate, the higher the NPV, the more profitable is the project.

b) Internal Rate of Return (IRR) may be defined as the discount rate that makes the present value of future cash flows of an investment project equal to the cost of the project. Alternatively, IRR may be considered as the maximum rate of interest that could be paid for the capital employed over the life of an investment without loss on the project. Therefore, when the discount rate in the NPV calculation is

equal to IRR, a zero NPV is obtained.

c) Breakeven Analysis is divided into two sections namely the short term Breakeven (B/E), and a Breakeven condition with the potential to achieve a particular rate of return. The short term B/E analysis allows a decision to be made between operating and shut-down. It will be an out-of-pocket cash B/E price which includes only the variable costs of production and the cash fixed costs in its calculation. The second B/E analysis allows the recovery of the capital investments and a particular rate of return, apart from variable and fixed costs of operation (179). A form of sensitivity analysis is also performed using the second, long term, B/E technique, whereby a B/E value for each of the variables involved is calculated which will yield a zero NPV. The percentage changes from the original values are then calculated for the variables, which may subsequently be used as a measurement of sensitivity.

More detailed descriptions of the above techniques are contained in Appendix H, together with a computer program capable of performing these analyses (Except long term breakeven analysis). The derivation of the expressions to calculate the long term B/E values can also be found in Appendix H.

d) Investment Simulation technique is used to overcome the serious limitation of changing only one variable at a time while leaving all other variables unchanged as in the sensitivity analysis described above. This is not fully representative of the real situation. The simulation technique employed makes provision for simultaneous variations of all the variables. The variables used in this technique are in the form of probability distributions, instead of the usual single value parameters. The probability distributions of the variables ensured that a more realistic market situation is represented by giving the most likely outcomes of the variables the highest probabilities, hence making them more significant. The NPV of a randomly selected set of variables (from the probability distributions of the variables) is then calculated. This procedure of variable selection and NPV calculation are repeated a large number of times (about 100,000 times). The probability distribution of the NPV's calculated is then constructed, which is the output of the simulation.

This technique is described in reference (180). The version adapted for

present work is discussed in Appendix I, together with details of the probability distribution derivations and the description of the computer program developed.

An attempt has been made to establish forecasts for the variables involved in the investment simulation throughout the life of the project. Leading indicator technique coupled with trend line fitting have been used for variables where an leading indicator can be established, such as cost of capital equipment. For variables which are complex and requiring very substantial in depth study before forecast of any accuracy can be derived, such as cost of electricity, rubber crumb prices, fixed and labour costs, a high-low bound technique or a fixed rate of increase has been employed. These forecasted values have been incorporated into the investment simulation program (similar to that described in Appendix I). However, it is questionable if the introduction of forecast data are of value, given that the simulation (without forecasted data) generates a small positive NPV, (and that most costs will rise which would have an adverse effect on NPV), also that there exists an element of uncertainty and error in establishing the variable probability distributions and in forecasting future values of the variables, which will compound into an even greater uncertainty. This uncertainty is, at best, not easily quantifiable, if not impossible to do so. The interpretation of the results from this simulation will be very vague given these uncertainties. Hence, it is reckoned that such an exercise requires far more thorough study, and it is not possible to complete such an thorough going programme within the time constraint of present investigation.

B. Results and Discussions

The economic analysis was carried out with the cost data contained in Appendix G using the two computer programs described in Appendices H and I.

In the NPV/IRR calculations, it is assumed that the average capacity utilisation of the plants is 70% of the design capacity, and an interest rate on a loan sufficient to finance the investment of 10% after tax (approximately equivalent to 20% before tax) net of inflation (the derivation of this discount rate estimation is discussed in

Table 7.1 Summary of NPV⁺ and IRR for Plant III

PLANT	CRUMB PRICE (£)	NO TAX		TAX RATE = 52%	
		NPV ⁺ (£)	IRR (%)	NPV ⁺ (£)	IRR (%)
I	160	- 937,797	0	-1,065,517	0
	170	- 830,210	0	- 907,836	0
	180	- 722,622	0	- 750,154	0
II	160	- 553,363	0	- 545,305	0
	170	- 502,039	3.3	- 261,836	1.7
	180	- 450,715	12.3	- 67,240	7.7
III	160	- 100,222	17.0	40,010	11.1
	164	28,882	20.9	146,153	14.1
	170	222,539	26.5	303,464	18.7
	180	545,300	35.6	561,364	26.1
IV	160	- 427,831	4.5	- 258,269	2.5
	170	- 169,621	14.2	- 29,472	9.1
	180	88,587	22.9	184,679	15.8

⁺ NPV at 20% discount rate before tax, and 10% after tax.

Section 7.3 D). Capital allowance in the NPV/IRR calculation is offset against the taxable income generated by the investment.

The plant is assumed to have a zero scrap value at the end of year ten, the estimated life of the plant.

a) NPV and IRR

The results of the NPV (at a discount rate of 20% before tax and 10% after tax) and IRR calculations for the four plant combinations (see Section 7.3A) are summarised in Table 7.1. A range of output price of £160 to £180 per tonne of rubber crumb has been used.

It is seen from Table 7.1 that plant combinations I and II both generate negative NPV even at optimistic output prices. Plant I has negative cash flows hence would have infinitely large negative IRR, while plant II has an IRR of about 8% (after tax) at output price of £180. A characteristic of the process seems to be a low contribution (Sales Revenue - Variable Costs) per tonne of output and high fixed costs in relation to capacity. Plants with large capacities are therefore required so that a high volume output and the corresponding high total contribution can be generated to earn fixed costs and show a potential for recovering capital costs. Plant combination I has a low volume output hence has a low total contribution. The fixed costs of the plant (I) represents 27.4% of the total operating costs at full capacity output. Plant II does not generate a positive NPV over the output price range considered and only an IRR of less than 10% (after tax) at optimistic price of £180 which is insufficient to recoup the capital invested. This non-profitable situation of plant I and II is much the same for the before tax cases. Plant I and II can therefore be dismissed as economically non-feasible on the ground discussed above. The analysis which follows therefore omitted plant I and II.

A positive NPV is generated by plant III at output price of £170 or more per tonne. It also generates an IRR of 14.1% (after tax) at this price level. Plant IV requires an output price of £180 to realise a positive NPV and an IRR of greater than 10%(after tax). Comparing plant III and IV on these basis, plant III is comparatively more profitable than IV. Despite a saving of about £60,000 in capital outlay, the relatively smaller output capacity of plant IV (some 2000 tonnes

per annum less than plant III), result in a high fixed costs per unit output and loss in total contribution. A list of NPV at a range of discount rates of 5% to 20% for plant III and IV is presented in Table 7.2 and 7.3.

From the above discussions, it appears that plant combination III with a three TPH (tonne per hour) ND system and a three 2-H mills KEK-BOC system is the most economically feasible combination. To sustain such a plant in both tax cases (i.e. 20% before tax and 10% after tax), and without losses, the composite price of output rubber crumb must be £160 or more per tonne. The plant will have a NPV of about £303,500 at a discount rate of 10% (after tax) and output price of £170 per tonne, operating at 70% of full capacity, and it will generate an IRR of about 19% after tax. At £160 per tonne, plant III generates an NPV of about £40,000 and IRR of about 11%. Given that the required after tax interest rate is about 10% and that the composite price for the output is £164 per tonne (see Section 7.3 C), this plant appears very promising. Further analysis will be carried out on plant combination III only.

b) Breakeven Analysis and Sensitivity Analysis

The short term out-of-pocket breakeven (B/E) prices and volumes for plant III are presented in Table 7.4. At these output prices and volumes, there is no provision for the recovery of the cost of the capital invested nor the capital outlay. The short term B/E price consists of the variable and operating fixed costs which is just sufficient to keep the plant in operation.

Table 7.4 Short Term Breakeven Price and Volume for Plant III

Tax Rate = 52 %

At Price	B/E Volume	At Volume	B/E Price
128	10401	6158	141
144	5802	6928	138
160	4023	7698	135
170	3079	8468	132
192	2494	9238	130

At output volume of 7698 tonnes per annum (i.e. at 70% of full design capacity), the short term B/E price is £135 per tonne.

Table 7.2 NPV for Plant Combination III

DISCOUNT RATE (%)	NPV @ 10% TAX RATE = 52%			
	PRICE OF CRUMB OUTPUT			
	£160	£164	£170	£180
5	256,637	380,554	565,228	870,314
6	207,421	327,367	505,911	800,390
7	161,399	277,597	450,365	734,867
8	118,309	230,968	398,287	673,395
9	77,917	187,229	349,403	615,657
10	40,010	146,153	303,464	561,364
11	4,392	107,533	260,242	510,255
12	-29,111	71,181	219,533	462,088
13	-60,663	36,927	181,147	416,646
14	-90,407	4,613	144,913	373,729
15	-118,477	-25,902	110,675	333,156
16	-144,996	-54,748	78,288	294,758
17	-170,074	-82,044	47,623	258,384
18	-193,813	-107,900	18,558	223,893
19	-216,307	-132,414	-9,015	191,155
20	-237,642	-155,680	-35,199	160,055

Table 7.3 NPV for Plant Combination IV

DISCOUNT RATE (%)	NPV @ 10% TAX RATE = 52%		
	PRICE OF CRUMB OUTPUT		
	£160	£170	£180
5	-102,809	156,366	405,431
6	-138,533	114,115	355,403
7	-171,734	74,619	308,558
8	-202,630	37,656	264,639
9	-231,417	3,021	223,416
10	-258,269	-29,472	184,679
11	-283,348	-59,990	148,235
12	-306,797	-88,684	113,910
13	-328,745	-115,694	81,547
14	-349,317	-141,146	51,000
15	-368,615	-165,155	22,137
16	-386,739	-187,827	-5,162
17	-403,779	-209,257	-31,009
18	-419,817	-229,534	-55,505
19	-434,926	-248,738	-78,741
20	-449,174	-266,944	-101,805

Considering the current demand and prices, such a plant may be able to withstand a temporary or short term soft prices or low demand. However, if soft prices and/or low demand prevail, this plant will not be able to remain in operation.

On the contrary to short term B/E prices and volumes, the long term (L.T.) B/E values obtained by using expressions developed in Appendix H have taken into account the recovery of cost of capital invested and capital outlay, as well as the effects of taxation. As explained in Appendix H, these L.T. B/E values are values at which the project realises a zero NPV. This technique not only allows the required maximum or minimum breakeven values for a project to be calculated, but a sensitivity analysis to identify the variables which are most critical to the success of the project can also be performed. It should be noted that the L.T. B/E values are obtained by substituting a same set of initial values for the variables (Except the variables under consideration) into the appropriate equations.

Two extreme cases are presented, one with and one without taxation. As observed above (Chapter 2), the rubber tyres manufacturers have suffered reduced demand for their products in the past few years. Although they have experienced varying degrees of profitability, it is possible that they have insufficient taxable income to make use of capital allowances or even benefit from the deduction of the interest on a loan to finance the project. Hence, a no tax case is also presented. The long term B/E values are presented in Table 7.5.

The L.T. B/E values can be used as a managerial tool. For example, it can be seen that the capital cost may be allowed to increase by about £300,000 before reaching the B/E point. Hence additional equipment such as machinery for increasing productivity, may be installed. This may in turn reduce the variable costs and/or fixed cost, consequently improve the cash flow and the ultimate profitability of the investment. The long term B/E values may be considered as risk allowance indicators which provide the decision maker with a measurement of risks that the decision maker will be undertaking, at a particular set of conditions, before the investment reaches its breakeven point of $NPV = 0$.

Sensitivity factors can be calculated from the percentage changes of the critical B/E values from their initially assumed values. The smaller

this % change, the more critical is the variable in determining the profitability of the project. Hence, the variable with the smallest % change will have the highest sensitivity ranking. The sensitivity rankings for the variables are calculated and presented in Table 7.6.

It is seen from Table 7.5 and 7.6 that, in general, the critical values for the no tax case have a smaller change from the initially assumed values. This has a serious consequence that in the no tax case, the profitability of the project is more susceptible to unfavourable changes in the variables. Taking output crumb price as an example, a more than 0.5% reduction in price, or a more than £8 per tonne decrease, will render the project uneconomical. Whereas in the tax case, the critical output crumb price is £156.8 per tonne. The sensitivity rankings for the two cases, in general, are similar, with price of output being the most sensitive variable, followed by variable cost, capacity utilisation and fixed costs. The introduction of tax has made capital costs less critical. Given the current economic situation, it is more likely that a rubber recycling plant will be established as a dependent operation of a large company (see Chapter Two). Hence, the tax case is more probable in practice.

As stated above, the NPV is extremely sensitive to price fluctuation. Output price has a direct effect on the revenue. Given the weak demand in the present market situation, the fact that price of rubber crumb output is the most sensitive factor in determining the NPV of the project is not very encouraging. This depressed crumb price behaviour is reflected in the crumb price probability distribution used in the investment simulation (presented in Section I.3 (b) of Appendix I).

Variable costs is the second most sensitive factor. Any rise in variable costs, such as a fall in selling price, will lower the contribution and raise the breakeven level of output of the plant. The cost of liquid nitrogen is the major cost factor in the variable costs, consisting of 76% of the variable costs in plant combination III. This indicates the importance of efficient usage of liquid nitrogen. The liquid gas market is oligopolistic, with only two major liquid gas suppliers (Air Products and BOC). Favourable prices can be expected for the initial installations (of for example liquid nitrogen storage tank, insulated pipe-line etc), as each liquid gas supplier is competing to secure the contract to supply the future liquid nitrogen requirements. However, after the

Table 7.5 Long Term Break-Even Values for Plant Combination III

VARIABLE	INITIALLY ASSUMED VALUE	NO TAX CASE B/E VALUE	TAX CASE B/E VALUE
Output Price	£164	£163.1	£156.8
Variable Cost	£107.81	£108.68	£114.8
Fixed Cost	£210,000	£216,713	£266,021
Total Capital ^d	£934,522	£963,404	£1,250,102
Project Life	10	9	7 ^c
Capacity Utilisation	70%	69%	60.4%
Reqd. Return/Max. Discount Rate	20% || 10% ^a	21% ^c	16.3% ^c
No Tax Case	£29,091 ^b		
NPV Tax Case	£179,856	0	0

a 20% before tax; 10% after tax.

b No tax case £29,091; tax case £179,856.

c Determined by trial and error and interpolation.

d Total capital investment. The initial assumed working capital of £187,149 has been added to the initially assumed or B/E values.

Table 7.6 Sensitivity Factors derived from Long Term B/E Values

VARIABLE	NO TAX CASE		TAX CASE	
	SENSITIVITY FACTOR	RANKING	SENSITIVITY FACTOR	RANKING
Output Price	0.5%	1	4.4%	1
Variable Cost	0.8%	2	6.5%	2
Fixed Cost	3.2%	4	26.7%	4
Total Capital	3.9%	5	42.2%	6
Project Life	10.0%	7	30.0%	5
Capacity Utilisation	1.4%	3	13.7%	3
Reqd. Return / Max. Discount Rate	5.0%	6	63.0%	7

initial installation, the supply of liquid nitrogen will be tied to one supplier, and the cost of liquid nitrogen may not be varied favourably.

Lower capacity utilisation has the effect of reducing the volume of output and hence the total revenue and contribution. It is the third most sensitive factor in determining if the project is to command a favourable NPV. As discussed in 7.3C, the price of recycled rubber such as rubber crumb is particularly susceptible to demand. The capacity utilisation of a plant is also dependent upon demand for the rubber crumb output. It is observed that price and capacity utilisation variations are likely to move sympathetically which would result in an even greater adverse effect on NPV.

Fixed cost and total capital costs are the fourth and sixth rankings in sensitivity order. These may partly explain why the plant combination IV with a smaller capital outlay but higher unit fixed and variable costs is less profitable than plant III.

The relatively low sensitivity ranking of N, the project life reflects the importance of claiming capital allowance in the earliest possible period of the project, and that a smaller present value will be obtained for a later future income. The ranking of discount rate indicates that the NPV of the investment is not strongly affected by small changes in discount rate.

LIMITATIONS OF THE NPV/IRR, B/E AND SENSITIVITY ANALYSIS

The analyses performed above have several limitations which will be discussed below.

(i) The usual limitations of breakeven analysis are present, i.e. it is assumed that the cost functions follow a linear relationship, and costs and prices are assumed to be constants throughout the life of the project. The linearity of cost functions may fail when, for instance, there is a fall in capacity utilisation because perhaps of the drop in demand, the secondary grinding operation may move from three mills to more efficient use of two mills. Similar linearity assumptions have been made in estimating the various costs in Appendix G and I. Attempts to establish forecasts for the costs and prices has indicated that more thorough investigations in complex economic factors such as national economy, disposable income, and energy prices are needed for reasonably realistic forecasts. This unfortunately falls beyond the scope of the present study.

(ii) Sensitivity analysis has been carried out by varying one factor while holding the other factors constant. In practice, this may not be the case. Taking price of rubber crumb as an example, an increase in price is likely to lead to a decrease in demand (because of the interaction of supply and demand). A decrease in demand will induce a decrease in volume output and hence capacity utilisation of the plant. Similarly, an increase in demand will induce an increase in volume of output to satisfy the increased demand. However, if the volume output has reached its maximum, price of output may increase. This example demonstrates that some of the factors may be inter-related, and hence sensitivity analysis performed with variation in only one factor is not realistic. The example below shows sensitivity analysis in NPV carried out with a 10% change in price and capacity utilisation with initial price of £170 and capacity utilisation of 70% :

PRICE CHANGE (%)	CAPACITY UTILISATION CHANGE (%)	NPV @ 10% (£)	% CHANGE in NPV
0	0	303,464	0
-10	0	-153,031	-150
-10	-10	-276,011	-284
0	-10	149,690	- 50

Such a combined change in price and capacity utilisation has an even greater adverse effect on NPV, which unfortunately occurs in practice. Therefore, some means of analysis such as simulation which will take such effect into account may be used.

c) Investment Simulation

The result of the investment simulation for plant III is presented in Figure 7.2 and Table 7.7. Details of the input variable probability distributions and method of their derivation together with the computer program for the simulation are presented in Appendix I.

Under the assumed conditions, the expected NPV for the investment is estimated to be about £5,800. This may be translated into a slightly less than 1% gain over the initial capital outlay of about £0.93 million. This expected NPV value is smaller than the NPV calculated using single point estimates (see (a)). This can be expected given the conservative

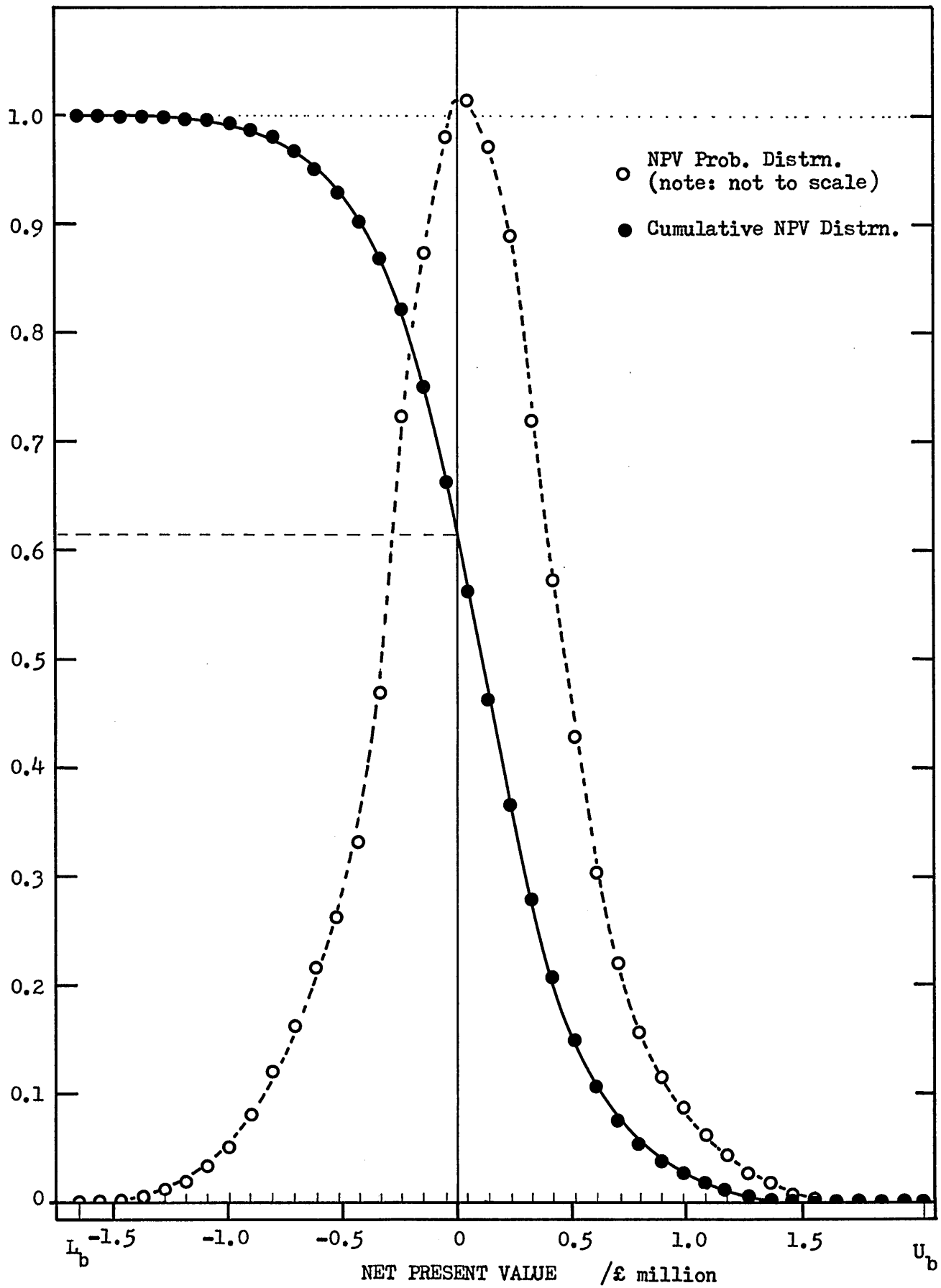


FIGURE 7.2 Investment Simulation Result for Plant Combination III.

L_b is the lower bound (-£1,743,097), U_b is the upper bound (£2,001,566).

Table 7.7 Result of the Investment Simulation

CLASS INTERVAL NO.	FREQUENCY	CUMULATIVE PROBABILITY
1	2	1.000
2	3	0.999
3	26	0.999
4	62	0.999
5	114	0.999
6	196	0.998
7	341	0.997
8	520	0.993
9	817	0.987
10	1203	0.980
11	1643	0.967
12	2164	0.951
13	2680	0.929
14	3329	0.902
15	4697	0.869
16	7236	0.822
17	8762	0.750
18	9802	0.662
19	10154	0.564
20	9698	0.462
21	8650	0.366
22	7198	0.279
23	5728	0.207
24	4298	0.150
25	3054	0.107
26	2202	0.076
27	1580	0.054
28	1170	0.038
29	875	0.027
30	635	0.018
31	427	0.012
32	289	0.007
33	181	0.004
34	109	0.003
35	68	0.002
36	37	0.001
37	23	0.0005
38	12	0.0003
39	7	0.0002
40	8	0.0001
<p> EXPECTED NPV = £ 5,786 STANDARD DEVIATION = £ 422,246 RANGE = £ 3,744,663 LOWER BOUND = -£ 1,743,097 UPPER BOUND = £ 2,001,566 CLASS INTERVAL = £ 93,617 </p>		

approach adapted in establishing the variable probability distributions which more closely reflect the real market situation (see Appendix I).

The standard deviation for the NPV distribution is calculated to be £422,246. This is small, considering the wide range of the distribution (about £3.7 million). The standard deviation is about 11% of the range. This can be seen from the narrowness of the NPV probability distribution in Figure 7.2 (note that the distribution is shown as broken curve and is not plotted according to the scale).

The 90% confidence interval for the expected NPV is calculated to be £3583 to £7989. (NPV distribution approximated by a Normal distribution). The 90% confidence interval is again small, within $\pm 0.4\%$ of the expected NPV.

It can also be seen from the graph that the probability of achieving a positive NPV for this investment is about 0.62. In other words, this investment is less likely (38% chance) of failing to realise a positive NPV. Therefore, under the conditions described by the probability distributions of variables involved in this cryogrinding plants, there is a more than 50% chance of this plant achieving a positive NPV, and hence, if conditions prevail, such a plant can be considered as economically feasible.

C. Summary of the Implications of the Economic Analysis

The economic analysis performed in the previous section has indicated that plant combination III of the ND, KEK-BOC cryogenic grinding process is potentially the most economically viable plant. This plant commands an NPV (at discount rate of 10% after tax) of about £146,000 and an IRR of about 14%, at current (December 1981) composite output rubber crumb price of £164 per tonne and operating at 70% of full design capacity. At crumb price of £180 per tonne, it has an NPV (of 10%) of over £0.5 million and IRR of about 26%.

The analysis clearly indicates the dismissal of lower volume throughput plant combinations, I and II, as economically non-feasible. Plant IV requires an output price of greater than £170 per tonne in order to realise a positive NPV. Plant III is, therefore, tactically a better plant.

The long term B/E analysis yields a set of critical B/E values above or below which the project will not achieve a positive NPV. For plant III and with tax, the most crucial factor is the price of the output rubber crumb at 4.4% below the initially assumed price of £164 per tonne, and ranking first in the sensitivity analysis carried out. The sensitivity analysis also identified that variable costs, capacity utilisation and fixed costs are ranked in that order of importance.

The introduction of tax, with the project generating sufficient taxable cash flows, is to attract capital allowance, which is absorbed by the taxable cash flows. The net effect, as seen in Table 7.5 is the project generating a higher NPV. The tax implications, which are serious for the project, will vary according to the tax position of the company undertaking the project, and require a more detailed consideration than provided in this report.

The investment simulation carried out has shown that, under the prescribed conditions, the probability of plant III realising a positive NPV is about 62%. This indicates that if the conservatively established conditions remain, such an investment is economically feasible. A small expected NPV of about £5,800 at 10% discount rate after tax is obtained from the simulation.

The above analysis identifies that the economic feasibility of the cryogenic rubber grinding plants in the present study depends largely on four factors, namely price of rubber crumb output, variable costs of production, capacity utilisation and plant size. Before proceeding to discuss each of the four main factors, it is necessary to examine the structure of the rubber recycling industry more closely.

The structure of the rubber recycling industry is detailed in Chapter Two. This industry/market structure is comprised of the industries which supply it with input, and those that consume its output, recycled rubber. The main suppliers to the rubber recycling industry are the tyre retreaders and tyre merchants/dealers who supply both the scrap tyre and coarse rubber crumb to the industry. The supply situation of scrap tyre has been discussed in Chapter Three, and for the near future, there will not be any scrap tyre shortage. The supply situation regarding coarse crumb has been discussed in Section 4.2. Although a very convenient form of scrap rubber input, the supply of coarse crumb or tyre buffings are

comparatively very small and dependent upon the production of the tyre retreading industry.

The output recycled rubber is destined to an even more diverse spectrum of industries. These industries include tyre, tyre retreading, general rubber goods and sports surfaces industries, a discussion of which can be found in Section 7.5. The amount of recycled rubber consumed by these industries in turn depends on the production output of these industries, which can be related to the consumption of their output by the other industries. For example, the output of tyre industry can be related to car production, the state of art of tyre technology and the quantity of tyres imported and exported. Taking this inter-related chain further, the car production can again be related to the GNP and the disposable income of the population, and the amount of car imports and exports. The other main consumer of recycled rubber is the general mechanical rubber goods and products such as floor mat and carpet underlay. The production of general rubber goods may again be related to the GNP and the disposable income of the population. The production of carpet underlay obviously depends on the carpet production which in turn may be related to the number of new houses, offices, factory and buildings built. Although carpet underlay consumes a considerable amount of rubber crumb, the use of crumb in this application is facing severe competition from other underlay materials. With the brief discussion of the market/industry structure for the rubber recycling industry above, we may then proceed to discuss each of the four main factors affecting the economics of the cryogrinding of scrap rubber tyres.

a) Rubber Crumb Price

As identified by the sensitivity analysis, the price of rubber crumb is the most influential factor governing the NPV. Price of rubber crumb is very much dictated by its demand (see discussion on price in Section 7.3 C). The present low derived demand (due primarily to the current recession and state of rubber industry) has prevented rubber crumb from commanding a higher price. This soft crumb price is expected to last for the near future (see Section 7.3 C). However, should demand recover, through for example establishing new markets for the crumb with new products based on rubber crumb and increased percentage of crumb incorporation (through a better understanding of the rubber-rubber composite properties, see Chapter 5) into rubber compounds, its price might then be more stable and

perhaps higher than present. However, the chances of a higher and stable price seem to be slight, until the capacity of rubber tyre manufacturing industry has been shown to equate with demand. The demand of rubber tyre is very much dependent upon the motor car production by the car industry. The possible markets for rubber crumb, and hence its demand, are discussed in Section 7.5.

b) Variable Costs

Variable costs rank second in the sensitivity analysis (on NPV). Liquid nitrogen (LIN) cost is by far the most important constituent cost of the variable costs, comprising 76% of the total variable costs for plant combination III. Thus, more effort should be concentrated on the efficient usage of LIN, such as through a more effective freezing tunnel design especially for the secondary grinding stage (which has a very high LIN usage rate of 0.8 Kg of LIN per kg of input coarse crumb). An improvement in LIN usage rate from 0.8 to 0.4 would reduce the total variable costs (for plant combination III) by £270,000 per year (cf. £541,000p.a.). Such as a possible reduction on the number of LIN storage tanks required, hence reducing the fixed tank rental cost. The prospect for LIN usage improvement is good, as the data used in the calculations is based on experimental work on a particular tunnel design (which may not be the most efficient for freezing rubber). Further work along this line is highly desirable.

The longer lasting radial tyres and the possible introduction of long life (100,000 mile) tyres (183) can have serious consequence on the tyre industry. In the long term, the longer lasting tyres will not only reduce the demand for new tyres, but also will seriously decrease the amount of scrap tyre arising. This will affect the cost of the scrap tyres themselves as well as increasing the cost of collecting them which in turn will cause the variable cost of recycled rubber process to increase. The effect of long life tyres is far reaching, as it will not only increase the cost of input scrap tyre, but will also decrease the demand for new tyres. Decreasing demand of tyres will, in turn, causes a decrease in demand for recycled rubber crumb (as tyre is one of the main recycled rubber containing rubber products) and will eventually alter the structure of the tyre and rubber recycling industries.

c) Capacity Utilisation

An increase in capacity utilisation has a direct effect on increasing the volume of output, decreasing the fixed cost per unit output, and increasing the revenue. As demonstrated above, capacity utilisation is

strongly demand dependent, which in turn depends on a wide reaching factors such as the economic health of the rubber processing industry, prices of rubber crumb and the general economic situation of the industry as a whole.

d) Plant Size

The effect of plant size is apparent from the NPV/IRR calculations. The smaller throughput and relatively high fixed cost result in a low total contribution which barely sufficient to offset the fixed cost. Coupled with high capital costs, the smaller plants i.e. plant I and II, fail to generate a positive NPV (at 10%) and realistic IRR even at a currently quite unrealistically high crumb price of £180 per tonne. This has the implication that the installations of smaller capacity in-house recycling plants (for factory scrap, for example) would not be economically advantageous.

As well as the measurable variables considered in the economic analysis, there are several important indirect or not easily quantifiable factors which may be taken into consideration. The following set out to discuss some of these factors.

Location Factor : Although the location factor is not included in the economic analyses, it cannot be ignored, and may be the most important factor. The economic analyses performed above assume that there is an abundant supply of scrap tyres and they are free for the taking, hence the cost of scrap tyres is that of transporting them. This assumption can only be true if the recycling plant is located within a reasonable distance of an area of relatively dense population, such as in the South East region.

The transport costs for scrap tyres represents about 8.5% of the total manufacturing costs for plant combination III. Thus, if the plant is not located in a favourable location, the rise in transport cost and instability of supply of scrap tyres would probably render the plant uneconomic.

Energy : Energy consumption/conservation associated with recycling scrap rubber can be classified into three main categories : (i) energy used to generate usable recycled rubber; (ii) energy saving in using recycled rubber during further rubber product manufacture; and (iii) the overall

energy saving in using the otherwise scrapped rubber.

The electrical power consumption required to generate recycled rubber product by cryogenic grinding technique is very low compared with that consumed by a conventional rubber reclaiming process. The electrical power consumption of plant III represents a mere 5% of the total manufacturing costs (cf 18% for reclaimator process (45)). However, the total energy consumption by a cryogenic grinding process should include the energy used in liquid nitrogen production (which is essentially the electrical energy used in converting the gaseous air to its liquid components).

Energy saving can be realised during the processing stages of a rubber compound incorporating recycled rubber (28) eg. during mixing and extruding stages. If powdered recycled rubber, such as rubber crumb, is used in powdered rubber technology, further advantages of low energy consumption, better mixing characteristics and shorter mixing time may be realised (184).

It has been stated that the use of recycled rubber should produce a net energy saving, considering the industry as a whole (67). To see the effect on overall energy saving by recycling rubber, consider a small quantity of scrap rubber eg. a scrap worn tyre. Rubber has a high calorific value, hence the scrap tyre can be burnt to obtain the locked in heat energy input into making the rubber from its most fundamental raw material such as crude oil, will be wasted. It would be easier and less costly to use crude oil as a fuel source. Conversely, by reusing the scrap rubber, an overall energy saving will be realised.

Clearly, a balance has to be established between the energy required to generate the usable recycled rubber and the energy savings that can be realised.

Environmental Effects : Scrap rubber, the majority of which is in the form of scrap vehicle tyres, is non-biodegradable. This makes it unsuitable for landfilling although many scrap tyres have found their way in rubbish tips. It has been reported (58) that 50% of the 25 million scrap tyres generated in the UK were unaccounted for. These 'unaccounted for' scrap tyres were mainly due to : (i) transition between tyre depots; (ii) 'lying around' in garages, gardens etc; and (iii) land filling.

Assuming that half of these scrap tyres were in transition between depots, there were about 6 million scrap tyres which were potential environmental pollutant or were already polluting the environment.

Disposing of scrap rubber tyres poses an environmental problem, and storing large quantities of these tyres not only poses a serious problem, it also constitutes a potential fire hazard. Burning of this scrap rubber for heat energy is not only wasteful, it also requires additional fuel to assist in their combustion process. Recycling of scrap rubber on the other hand, solves the undesirable environmental effects as well as saving the waste disposal costs.

Import Reduction : The use of recycled material, be it rubber, metal or paper, conserves valuable raw material. If the raw material has to be imported, such as rubber, recycling of the material will reduce its import. A reduction in raw material imports would have a favourable effect on the balance of payment for the country.

The conservation of virgin rubber through using recycled rubber can be estimated. Assuming a 10% recycled rubber incorporation, the net saving will only be about 5% as the majority of the rubber compounds used presently have incorporated about 5% of recycled rubber for processing considerations. Therefore, in 1979 (total virgin rubber consumption of 440,400 tonnes of which 30% was imported natural rubber and about 6.5% was imported synthetic rubber), a possible 22,020 tonnes of virgin rubber would have been conserved. This may be translated into an almost £5 million in import reduction (assuming average natural rubber price of £607 per tonne and £618 for synthetic rubbers in 1979, see Figure 2.5). The amount of virgin rubber to be conserved is very much dependent on the most likely recycled rubber incorporation rate that the rubber processors are willing to use, which at present is well below 10%.

Employment : The establishment of a manufacturing plant would have its associated employment elements, eg. the initial labour requirement for the construction of the factory building, for manufacturing the capital equipment and installing it, and the labour directly involved in the recycling plant. As estimated in Appendix G, plant combination III will create 24 employment vacancies directly. Indirectly, there will be labour requirement for collecting and transporting scrap tyres, and for supplying other raw materials such as liquid nitrogen to the plant.

However, with the possible reduction in rubber import and production, there may be a negative employment effect in the related sectors such as dock-yard and transport workers.

7.5 Market Potential for Recycled Rubber Manufactured using New Technologies

As cryogenic grinding process has been identified as one of the most promising technologies, and the output of this process is rubber crumb of various sizes, the recycled rubber product considered here will be rubber crumb.

(a) Traditional Market for Recycled Rubber

The impact of incorporating recycled rubber into rubber compounds on compound cost can be shown by the simplified examples given in Section 7.6, using a technological model.

As indicated in Chapter Five, in general, the physical properties of rubber vulcanizates incorporating recycled rubber tend to decrease with increasing levels of recycled rubber. Burgoyne et al (14) have indicated a figure of 10 phr of recycled rubber before there is a significant deterioration in physical properties. However, with an appropriate adjustment in curing system, Swor et al (27) have shown that a significantly higher recycled rubber loadings (up to 50 phr) can be incorporated with acceptable physical properties using their micronized rubber crumb (see Chapter Five). Hence, the potential usage of rubber crumb in this market sector depends largely on the quantity of recycled rubber that can be incorporated into the rubber compounds, which in turn depends on the technology and understanding of rubber compounds and vulcanizates incorporating recycled rubber.

Another possibility of increasing the recycled rubber content of rubber products is by legislative interference. In the USA, the Department of Energy was entrusted to set target for voluntary recycled rubber usage under the Recycled Targets Provision of the National Energy Conservation Act (1978) (187). Targets of between 5% for tyres and tubes to 15% for rubber footwear were set for 1987. Although the effectiveness of such legislation is arguable, it would encourage rubber processors to incorporate recycled rubber into rubber products which for one reason or another do not contain any recycled rubber.

Although present study restricts the scope to the use of recycled rubber

in rubber products, the rubber crumb produced by the cryogenic grinding process can be sold in the traditional crumb markets such as for carpet underlay and sports surfaces which use considerable amount of rubber crumb (of larger sizes). Recycled rubber has also find its use in rubberised asphalt for pavements and roofings, and rubberised road surfaces which have reported to be superior (188, 189).

b) European Market Potential for UK Recycled Rubber Producers

This is a very interesting aspect for the UK recycled rubber manufacturers to explore. The larger European market provides potential for plants to obtain sufficient volume of work to be economical. The rubber crumb price in Europe is also generally higher than that in the UK. For example, it was reported that the price per tonne of a relatively coarse crumb in Germany is about 40% higher than the present UK price for a similar grade (121). On the negative side, the additional transport cost to Europe may be prohibitive or may restrict the market to the neighbouring countries such as France, Belgium and Holland.

7.6 Compound Cost-Property Relationship of Rubber Vulcanizates Incorporating Recycled Rubber

The following is an attempt to study the cost-property relationship of rubber vulcanizate incorporating recycled rubber crumb, using a technological model. The model can be used to analyse the influence of cost and amount of recycled rubber on the compound cost under a specific set of compound design criteria. The model has been used on plastics products incorporating scrap plastics (208).

As seen in Chapter Five, the effect of recycled rubber incorporation on the physical properties of vulcanizates is varying, and the effect differs from rubber to rubber. In order to carry out this analysis, it is necessary to make simplifying assumptions relating to product specification, and the influence of recycled rubber on the physical properties of the vulcanizate. These assumptions are needed, primarily because of the lack of suitable technological models to describe the physical properties of vulcanizates with and without recycled rubber incorporation.

A single parameter criterion is adopted for the vulcanizate physical property specification. The most commonly specified physical property of tensile breaking load is chosen. That is the tensile breaking load of the rubber component of vulcanizate incorporating recycled rubber must be the same as that made from virgin rubber vulcanizate. Since the physical properties of recycled rubber incorporated vulcanizates will differ from that of the virgin vulcanizate, it is necessary to modify the product design when recycled rubber incorporated vulcanizates are used.

Consider a slab of rectangular cross-section, with width w and thickness t , the tensile breaking force is given by

$$F_B = \sigma_B w t$$

where σ_B is the tensile strength of the material.

Considering two vulcanizate slabs with unit width, one consists of virgin rubber only and the other with recycled rubber incorporation. For the same breaking force, the ratio of the slab thickness can be calculated by

$$\begin{aligned}
(F_B)_c &= (F_B)_v \\
(\sigma_B)_c \text{ w t} &= (\sigma_B)_v \text{ w t}_v \\
\frac{t_c}{t_v} &= \frac{(\sigma_B)_v}{(\sigma_B)_c}
\end{aligned} \tag{7.1}$$

where subscripts v refers to virgin material and c refers to the mix incorporating recycled rubber.

It was found that (see Chapter Five) the strength property of some rubber vulcanizates incorporating recycled rubber followed a linear relationship with the volume fraction of recycled rubber incorporated, V_{RR} , according to the simple law of mixtures (equation 5.7).

$$(\sigma_B)_c = V_{RR} (\sigma_B)_{RR} + (1 - V_{RR}) (\sigma_B)_v \tag{7.2}$$

The material systems under present simplified analysis is assumed to follow this linear relationship. This equation can be simplified by expressing the tensile strength of the recycled rubber, $(\sigma_B)_{RR}$ as a function of $(\sigma_B)_v$,

$$\begin{aligned}
(\sigma_B)_{RR} &= K (\sigma_B)_v \\
\text{or } K &= \frac{(\sigma_B)_{RR}}{(\sigma_B)_v}
\end{aligned} \tag{7.3}$$

Substituting (7.3) into (7.2), the expression becomes,

$$(\sigma_B)_c = (\sigma_B)_v (1 - (1 - K) V_{RR}) \tag{7.4}$$

The cost of compound for the slab based on virgin rubber can be expressed as:

$$C_v = V_v c_v \tag{7.5}$$

where V_v is the volume of the compound and c_v the unit volume cost of the compound. c_v consists of costs of all the compounding ingredients i.e. rubber, zinc oxide, stearic acid, sulphur, accelerators, antioxidant etc.

The cost of compound for the equivalent slab with recycled rubber incorporation is given by:

$$\begin{aligned}
C_c &= (V_{RR} c_{RR} + (1 - V_{RR}) c_v) V_c \\
C_c &= (V_{RR} c_{RR} + (1 - V_{RR}) c_v) V_c
\end{aligned} \tag{7.6}$$

where

where c_{RR} is the unit volume cost of the recycled rubber.

The ratio of the costs of compounds with and without recycled rubber incorporation can be obtained by dividing (7.6) by (7.5):

$$\begin{aligned}\frac{C_c}{C_v} &= \frac{(V_{RR} c_{RR} + (1 - V_{RR}) c_v)}{c_v} \frac{V_c}{V_v} \\ &= (V_{RR} \frac{c_{RR}}{c_v} + (1 - V_{RR})) \frac{V_c}{V_v}\end{aligned}\quad (7.7)$$

For slabs of equal width and length, and from equation (7.1),

$$\frac{V_c}{V_v} = \frac{t_c}{t_v} = \frac{(\sigma_B)_v}{(\sigma_B)_c}$$

Hence, (7.7) becomes,

$$\frac{C_c}{C_v} = (V_{RR} \frac{c_{RR}}{c_v} + (1 - V_{RR})) \frac{(\sigma_B)_v}{(\sigma_B)_c} \quad (7.8)$$

Substituting (7.4) into (7.8),

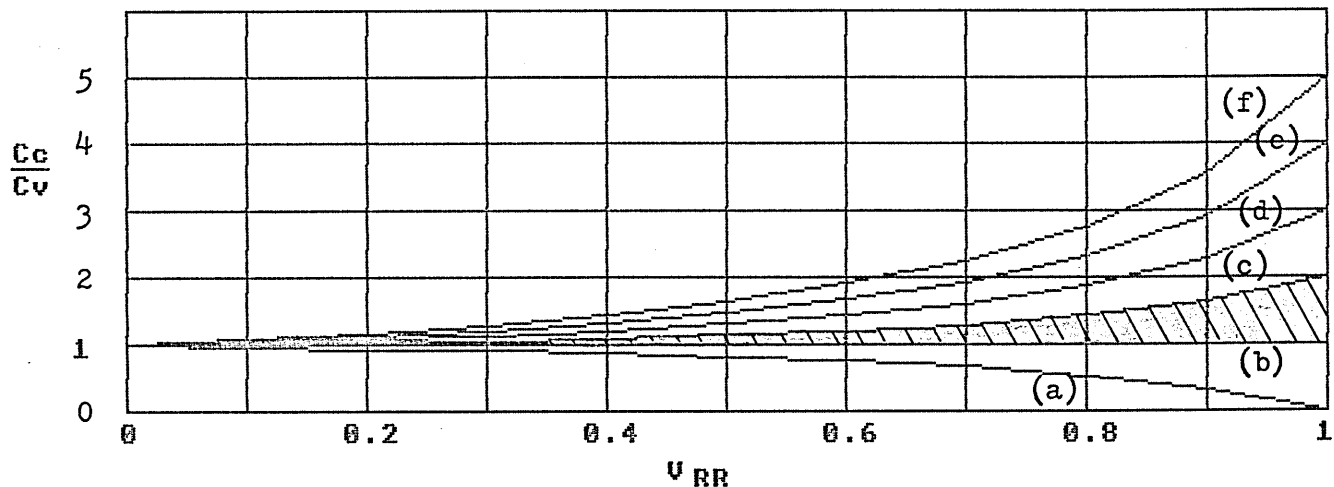
$$\frac{C_c}{C_v} = \frac{V_{RR} \frac{c_{RR}}{c_v} + (1 - V_{RR})}{1 - (1 - K) V_{RR}} \quad (7.9)$$

For practical cases, C_c/C_v ratio must be less than unity in order that the incorporation of recycled rubber will generate a saving in compound cost. From the model described by equation 7.9, it follows that the cost term, c_{RR}/c_v is desirable to be small. A small c_{RR}/c_v requires a low recycled rubber price, hence, it is in direct conflict with the requirement for economic feasibility of a rubber recycling plant.

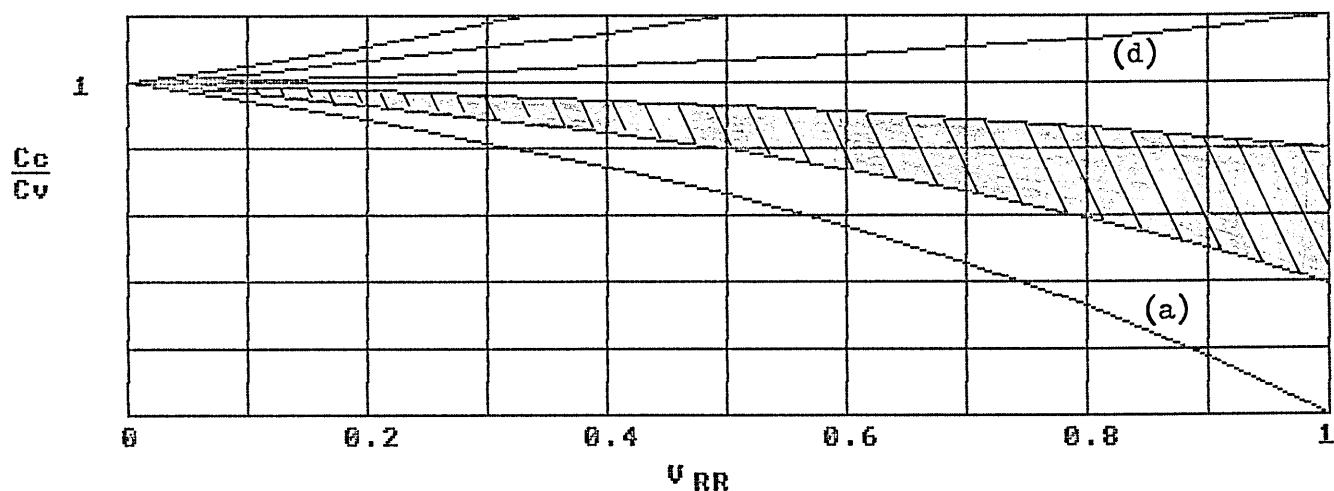
The value of K depends on values of $(\sigma_B)_{RR}$ and $(\sigma_B)_v$. As discussed in Chapter Five, $(\sigma_B)_{RR}$, in turn, is governed by the tensile strength and service history of the scrap rubber from which the recycled rubber is derived, the recycling process and the product manufacture procedure.

Representative results of the relationship between C_c/C_v and V_{RR} given by equation 7.9 are presented in Figures 7.3 to 7.4. Discussions on these results are presented in a later section.

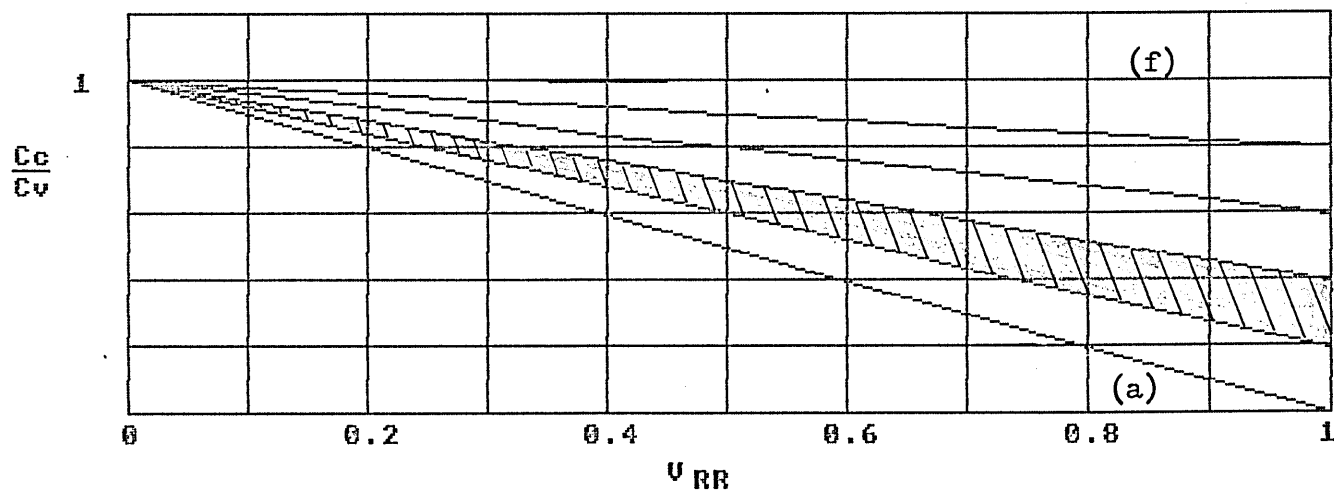
COST BENEFIT ANALYSIS FOR RECYCLED RUBBER - RUBBER COMPOUNDS



K value = 0.2 C_c/C_v axis = 1.0 per graduation.



K value = 0.5 C_c/C_v axis = 0.2 per graduation.

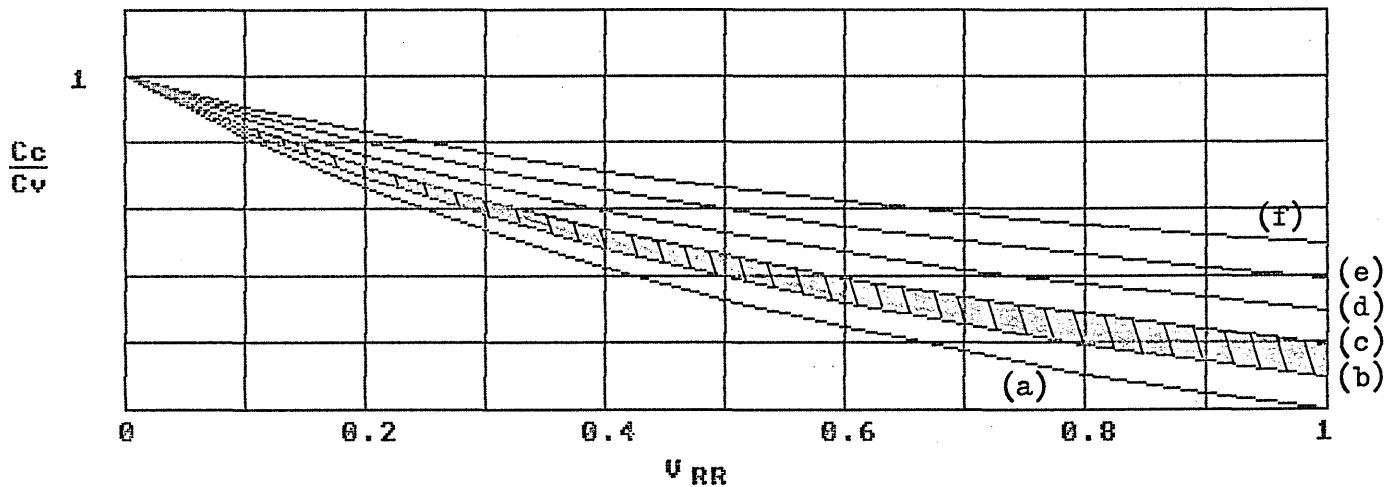


K value = 1 C_c/C_v axis = 0.2 per graduation.

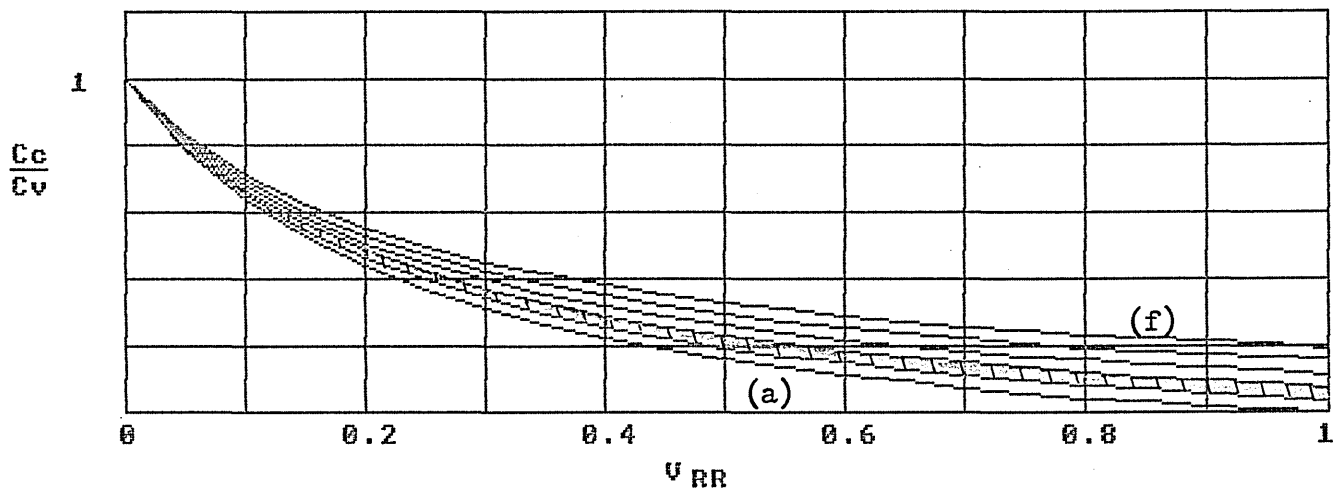
FIGURE 7.3 Compound cost-property relationships without curing agent adjustment consideration, equation 7.9.

$c = c_{RHC}/c_v$: (a) $c=0$; (b) $c=0.2$; (c) $c=0.4$; (d) $c=0.6$; (e) $c=0.8$
(f) $c=1.0$

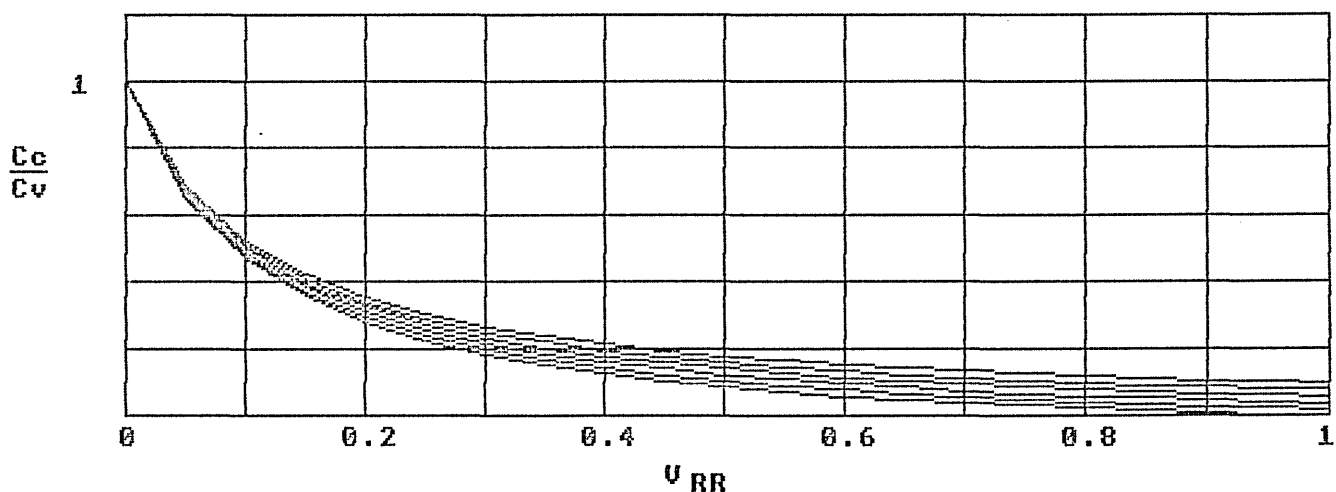
COST BENEFIT ANALYSIS FOR RECYCLED RUBBER - RUBBER COMPOUNDS



$K \text{ value} = 2$ C_c/C_v axis = 0.2 per graduation.



$K \text{ value} = 5$ C_c/C_v axis = 0.2 per graduation.



$K \text{ value} = 10$ C_c/C_v axis = 0.2 per graduation.

FIGURE 7.4 Compound cost-property relationships without curing agent adjustment consideration, equation 7.9 . $c = \frac{c_{RHC}}{c_v}$
 (a) $c=0$; (b) $c=0.2$; (c) $c=0.4$; (d) $c=0.6$; (e) $c=0.8$; (f) $c=1.0$

Equation 7.9, which was developed previously by other workers (208), can be applied to rubber-rubber composites provided variations in compounding ingredients are accounted for. Here we consider variations in sulphur curing agent content. As described in Chapter Six, the incorporation of recycled rubber into a rubber compound will cause the migration of sulphur from the base matrix into the recycled rubber particles. Sulphur level adjustment is therefore necessary in order to achieve optimum cure and hence optimum physical properties. This will, in turn, affect the unit volume cost, c_v for recycled rubber incorporated compounds. Hence, the unit volume compound cost terms in equations 7.5 and 7.6 no longer equate each other. The unit volume compound cost in equation 7.6 will include a larger sulphur cost contribution and can be redefined as :

$$c'_v = c_{RHC} (1 - V_s) + c_s V_s \quad (7.10)$$

where c_{RHC} is the unit volume cost of compound excluding the cost of sulphur and recycled rubber but including other ingredients; c_s is the unit volume cost of sulphur; and V_s the volume fraction of sulphur. It is necessary to relate the value of V_s for optimum cure to V_{RR} . This can be done using the data of Swor (27) for micronised crumb. The value of V_s at maximum $(\sigma_B)_C$ is plotted as a function of V_{RR} in Figure 7.5. Over the range of V_{RR} studied this can be approximated by the linear relationship:

$$V_s = G V_{RR} + (V_s)_o \quad (7.11)$$

where G and $(V_s)_o$ are constants depending on the material system, and in this case taking the values of 0.025 and 0.01 respectively.

Substituting 7.11 into 7.10, the expression for c'_v becomes:

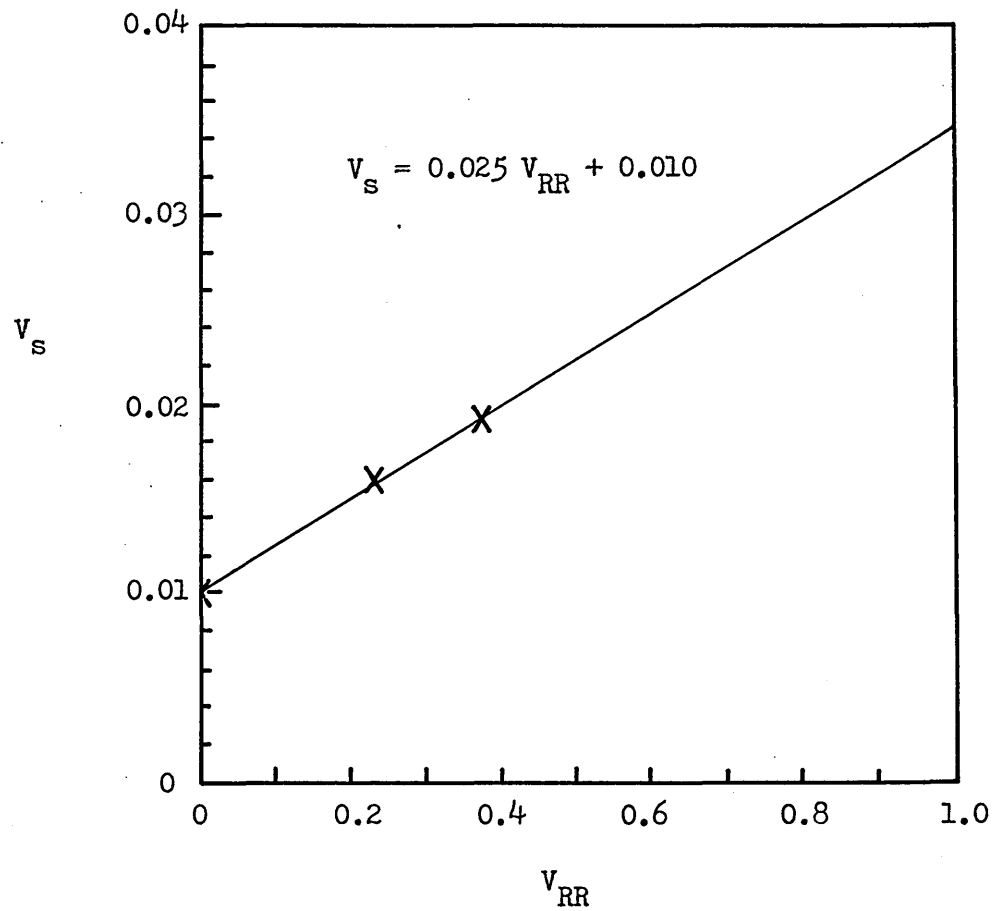
$$c'_v = c_{RHC} (1 - (V_s)_o - G V_{RR}) + c_s (G V_{RR} + (V_s)_o) \quad (7.12)$$

Replacing c_v in equation 7.6 by c'_v and following the subsequent steps, the ratio of C_c/C_v becomes:

$$\frac{C_c}{C_v} = \frac{V_{RR} \frac{c_{RR}}{c_v} + (1 - V_{RR}) \frac{c'_v}{c_v}}{(1 - (1 - K) V_{RR})} \quad (7.13)$$

Equations 7.12 and 7.13 have been used to develop a computer model based on the SBR compound recipe given in Appendix E.

Based on the prices of June 1981, the various cost terms



ϕ_{RR}	OPTIMUM SULPHUR LEVEL	V_{RR}	V_s
0	1.5 phr	0	0.010
50	3.2 phr	0.23	0.016
100	4.5 phr	0.37	0.019

FIGURE 7.5 Determination of Optimum sulphur level - V_{RR} relationship.
(Data from Swor et al (27))

for the compound recipe are calculated to be :

$$c_v = £ 707.64 \text{ m}^{-3}$$

$$c_{RHC} = £ 701.94 \text{ m}^{-3}$$

$$c_s = £ 1242.00 \text{ m}^{-3}$$

The constants G and $(V_s)_0$ assume the values 0.025 and 0.01 respectively, as determined for the material system of Swor et al. Representative results of the model with different recycled rubber crumb prices are presented in Figures 7.6 to 7.7 .

Discussions

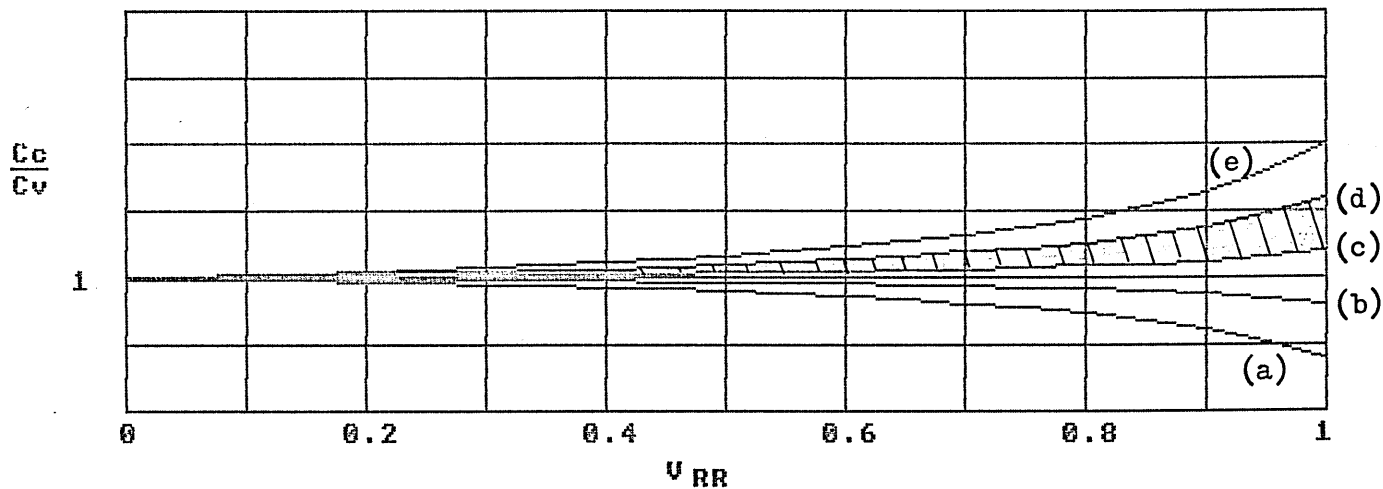
First, consider the model given by equation (7.9) which does not account for the additional cost of sulphur to compensate for the effect of curative migration. From the compounding information included in Appendix E, it can be calculated, for our SBR compound, that the range of c_{RR}/c_v of 0.2 to 0.4 corresponds to crumb price (per tonne) of about £125 to £250 respectively. This represents the practical c_{RR}/c_v range.

There are several features that can be observed from this model:

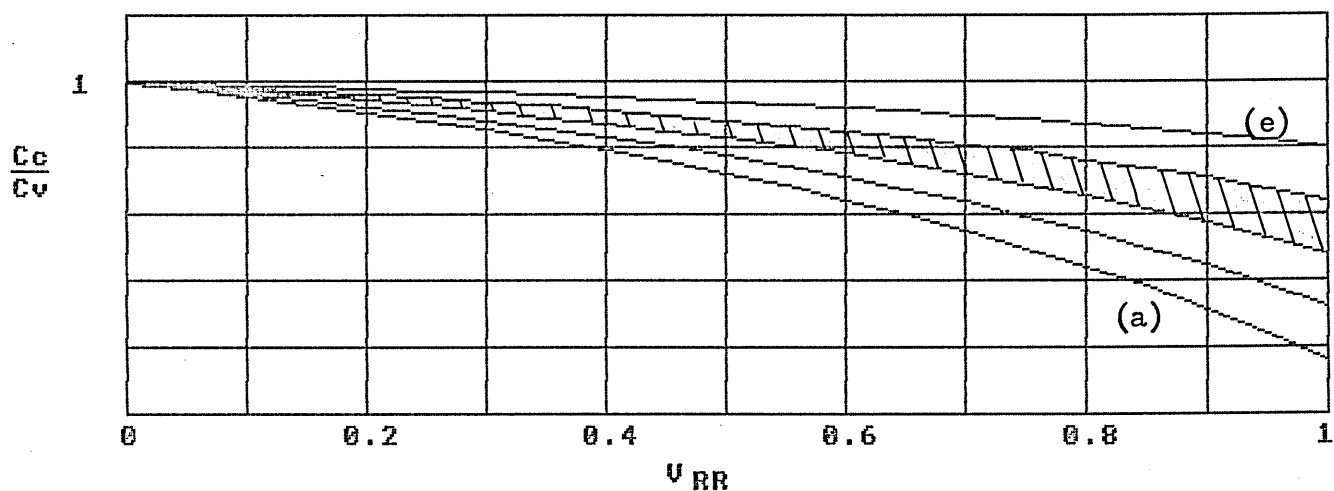
- (i) C_c/C_v ratio increases with increasing c_{RR}/c_v at all levels of V_{RR} and K . Therefore, c_{RR}/c_v should be as small as possible. In practical terms, this means a low recycled rubber price.
- (ii) At $K < 1$ and high c_{RR}/c_v ratio, C_c/C_v becomes > 1 i.e. a saving in compound cost will not be realised. For our practical c_{RR}/c_v range of 0.2 to 0.4, K must be ≥ 0.5 in order that C_c/C_v will be less than unity.
- (iii) At $K = 1$, linear relationships between C_c/C_v and V_{RR} are predicted by the model for all values of c_{RR}/c_v .
- (iv) At $K > 1$, all C_c/C_v values are below 1, indicating that a compound cost saving can be realised.

The $C_c/C_v - V_{RR}$ relationship becomes convex to the V_{RR} axis as K increases i.e. at high K , $C_c/C_v - V_{RR}$ line has a large negative gradient at low V_{RR} and the gradient gradually decreases as $V_{RR} \rightarrow 1$. For our SBR compound which has K of about 20, the model predicts an 80% compound cost saving at $V_{RR} = 20\%$, and a further 10% saving at $V_{RR} = 40\%$. It is recognized that this does not represent a practical situation. The unreinforced SBR represents a low strength matrix rubber.

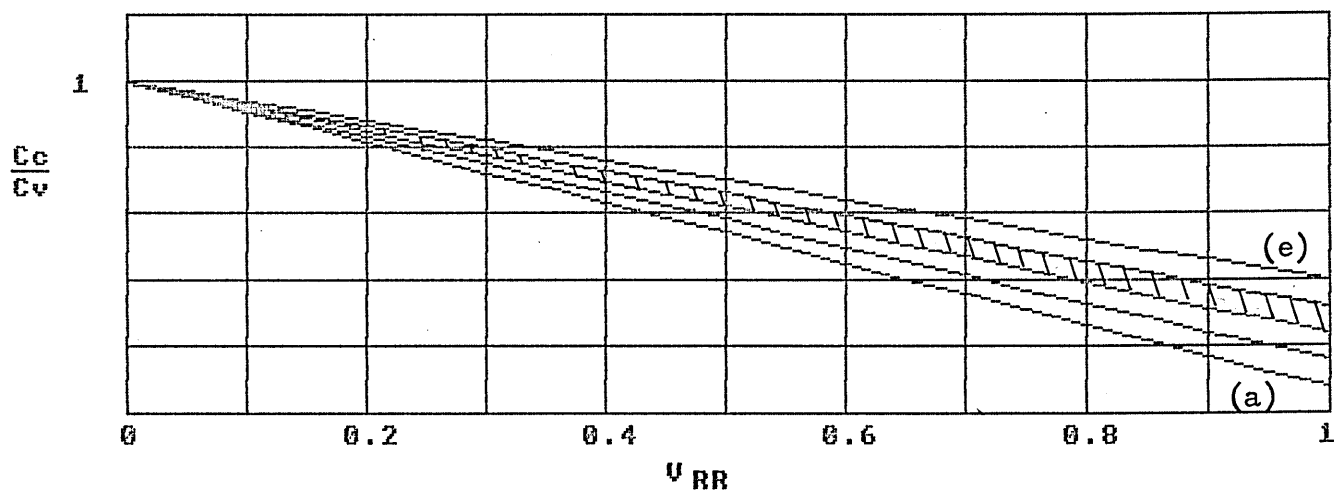
COST-PROPERTY ANALYSIS FOR RECYCLED RUBBER - RUBBER COMPOUNDS



K value = 0.2 Crumb price: £50 - £250 @ step of £50



K value = 0.5 Crumb price: £50 - £250 @ step of £50

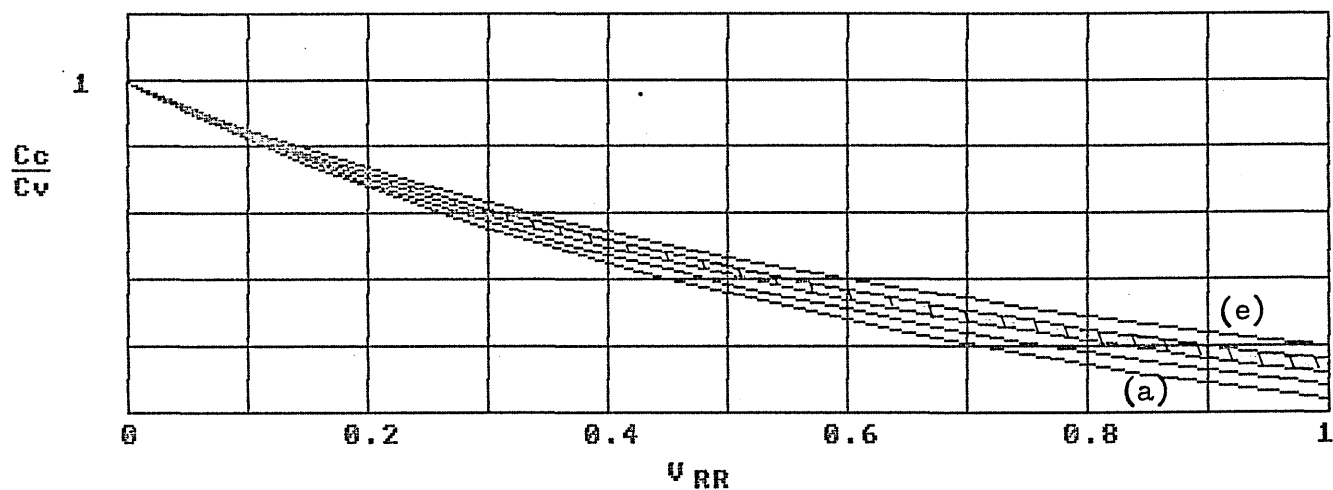


K value = 1 Crumb price: £50 - £250 @ step of £50

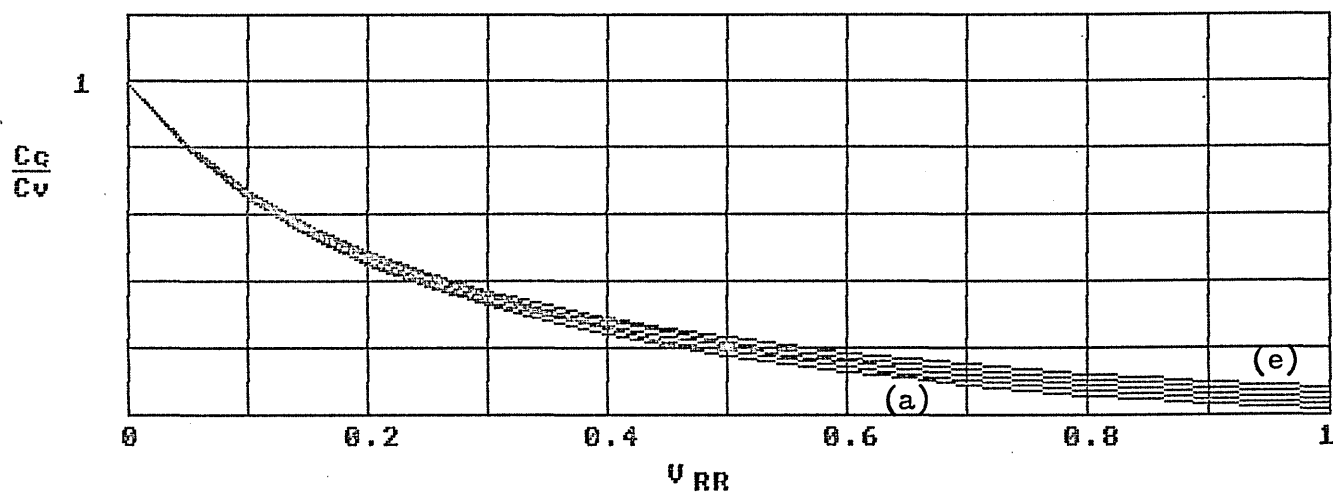
FIGURE 7.6 Compound cost-property relationships with sulphur curing agent adjustment consideration, equation 7.13.

Crumb price per tonne: (a) £50; (b) £100; (c) £150; (d) £200; (e) £250

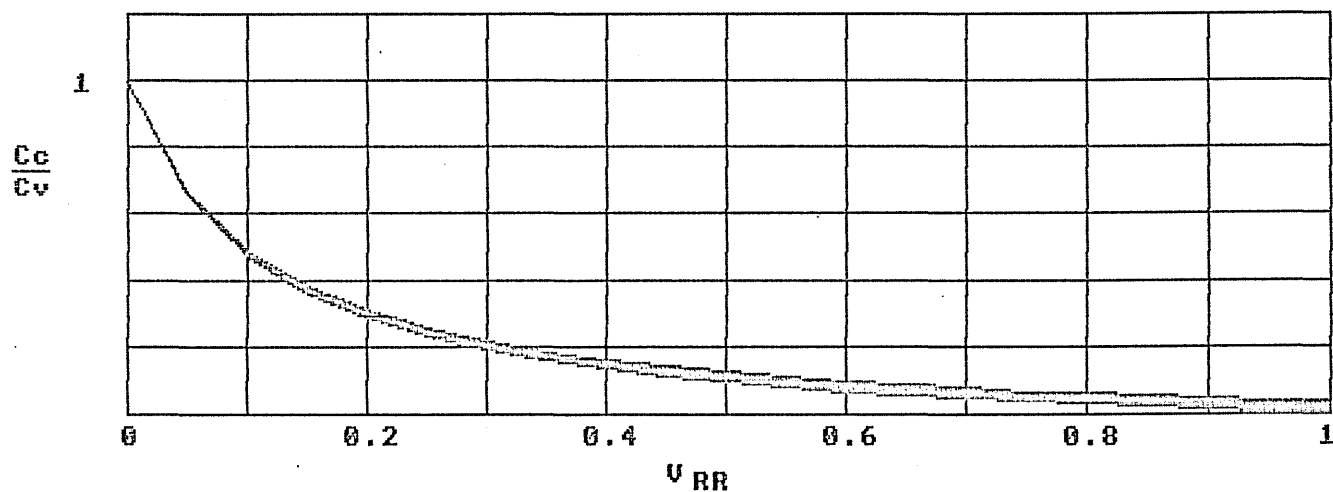
COST-PROPERTY ANALYSIS FOR RECYCLED RUBBER - RUBBER COMPOUNDS



K value = 2 Crumb price:£50 - £250 @ step of £50



K value = 5 Crumb price:£50 - £250 @ step of £50



K value = 10 Crumb price:£50 - £250 @ step of £50

FIGURE 7.7 Compound cost-property relationships with sulphur curing agent adjustment consideration, equation 7.13.

Crumb price per tonne:(a)£50; (b)£100; (c)£150; (d)£200; (e)£250.

The predictions of the second model (given by equation 7.13) are much the same as that of the first model i.e. C_c/C_v increases with c_{RHC} , and the K dependent of $C_c/C_v - V_{RR}$ relationship. However, there are some differences. The effect of c_{RR} on C_c/C_v is less profound when sulphur migration is taken into consideration. This is to be expected, as the contribution of c_{RR} to the total compound cost is less than that in the first model.

The effect of K value on $C_c/C_v - V_{RR}$ relationships is much the same as in previous model for the range of rubber crumb price (of £150 to £200 per tonne or about £171 to £230 per m^{-3}) investigated. The observations made for the first model are therefore also applicable.

It is recognised that both the models used are limited by the simplifying assumptions made, and in practical cases, there are other factors that need to be taken into consideration. Nevertheless, there are several important results that can be obtained from this analysis. They are :

- a) Effect of change in sulphur curing agent level to overcome sulphur migration has essentially no influence on compound cost;
- b) For the practical range in c_{RHC}/c_v (i.e. crumb price of £125 to £250 per tonne) the K value must be larger than 0.5. Whether such low property degradation can be achieved in practice is uncertain. Clearly, it will be less in cryogenically ground material than in ambient ground but the actual amount of degradation imposed on the RHC has never been measured. Intuitively, one would feel that degradation of tyre rubber during service and comminution would be at least a factor of 2 i.e. $K \leq 0.5$.
- c) At this minimum acceptable value of RHC degradation i.e. $K=0.5$, Figure 7.3 shows that an incorporation of 0.4 (or 85 phr) is needed to achieve a 10% saving in material cost. Bearing in mind that the model does not account for the cost of processing, it is clear that there is little economic justification for the use of crumb in high performance products.

The agreement between this result and current industrial practice provides some evidence for the validity of the model given in equation 7.9. This indicates that it might be possible to use it to investigate the long term situation with respect to the economic viability of reusing scrap rubber in an environment of rising energy cost and diminishing oil reserves.

8.1 Rubber Supply Situation

If current trends continue, there will be no shortage of supply of natural and synthetic rubbers in the near future. Recent investigations have shown that rubber producers in the UK, mainly manufacturing general purpose SBR, have been operating at about 45% of nameplate capacity (166). The historical data given in Chapter Two indicates that the price of synthetic rubber fluctuates in relation to the cost of crude oil. Despite price unification among OPEC nations in an attempt to stabilise oil prices (about a year ago), recent and current sluggish oil market has resulted in crude oil prices staying at fairly constant levels. With natural rubber, the intervention policy of the International Natural Rubber Agreement (an agreement endorsed by the natural rubber producing countries of the International Natural Rubber Council) has apparently not led to enhanced price stability in natural rubber, and prices have tended to decline. This price decline can be related to the decreased demand which has resulted from the continuing economic recession and the consequent lowered production in motorcar and tyre industries in most developed nations. The high interest rates of past few years had discouraged the maintenance of large rubber stocks (see 2.2(c) for example), hence contributed to the decreased demand. Given the sluggish crude oil market, soft demand for rubber and depressed rubber processing industry, especially the tyre sector, the prices of all general purpose rubbers are likely to remain at present level or may even decline (measured in real terms).

Owing to the continuing economic recession and the increasingly higher cost of petrol and other running costs, motorcar production in the UK has been decreasing (172). Motorists are also tending to use their vehicles less frequently. Together with longer lasting radial tyres, these factors not only contribute to the poor performance in the tyre industry through decreased tyre sales in both the original equipment and replacement markets, they have also resulted in a possible decrease in the supply of rubber scrap in the future. However, the existing vehicle population will ensure a sufficient and reliable supply of scrap rubber to the rubber recycling industry.

8.2 Rubber Recycling Procedures

Although there are currently several processes for the recycling of scrap rubber tyres, cryogenic grinding seems to be a promising alternative. The cryogenic grinding technology is sufficiently developed for further commercial exploitation, although the technology still needs to be significantly improved especially as regards liquid nitrogen consumption. Several cryogrinding plants are reported to have been installed (11, 12, 16). None of them are currently in operation. The only recycled rubber producer in the UK operates a version of the Digestor process (Uniroyal Ltd, Trafford Park, Manchester).

a) Forms of Input and Output of Recycling Processes

Three forms of scrap rubber input are commonly accepted by the majority of the rubber recycling processes. They are whole scrap tyre, tyre tread buffing, and crumb. All three are derived from scrap tyres and tyre products such as inner tubes, although rubber crumb may also be obtained from other sources such as factory scrap. The scrap tyre supply will contain an increasingly higher proportion of steel belted tyres. This will limit the input supply of the processes which are unable to handle this type of material input. The supply of tread buffings is particularly sensitive to its demand and the amount generated. The total amount of buffings generated is comparatively very small. Hence, the reliability of its continuous supply is questionable.

The two main forms of recycled rubber currently being produced are reclaimed rubber and rubber crumb of various sizes. Reclaimed rubber is produced mainly by the conventional recycling processes such as the Digestor and Reclaimator processes, although the Trellfax process also produces a form of reclaimed rubber. Rubber crumb in the size range of 10 to 300 mesh sizes is produced by a variety of grinding process. The majority of current supply of rubber crumb in the size range of 10 to 40 mesh is derived from tyre buffings. Rubber crumb will be a significant form of recycled rubber as processes showing commercial potential such as cryogenic grinding and Gould process yield rubber crumb.

b) Economic Analysis

The collection of reliable cost data has been the major difficulty, however, a relatively complete set of data has been obtained for a cryogenic grinding process. A detailed analysis has been performed. It

is found that under currently depressed rubber crumb price, and low demand, the most economically feasible of the four cryogrinding plants studied will not generate a positive NPV. At composite output crumb price of £160 per tonne, this plant combination III will generate a NPV of about £40,000 at a discount rate of 10% and an IRR of about 11%. This optimal plant has a throughput capacity of three tonnes per hour.

The sensitivity analysis performed on the cryogrinding process indicates that price of the output rubber crumb is the most sensitive factor in the NPV determination. The current unstable prices make the degree of uncertainty of the economic analysis even more. The variable cost ranks second in the sensitivity order, with cost of liquid nitrogen being the main component of the variable cost (about 76% for the optimal arrangement). Improving the liquid nitrogen usage, therefore will have a profound effect on variable cost, and subsequently improving the marginal contribution. Capacity utilisation and fixed cost are next on the sensitivity list.

Discount rate and plant size are also important factors. Higher rates will mean higher interest payments on capital loan, and in NPV calculations will result in smaller present values for future cash flows. The smaller plants, with throughput of one to two tonnes per hour, tend to have high fixed cost per unit output (due primarily to low output capacity), hence generating low revenue and low total contribution. Therefore, these smaller plants are economically unattractive. This has an important consequence in that it is not economically profitable to carry out low volume in-house scrap rubber recycling.

The sensitivity analysis using long term break-even technique has also indicated that capital cost is one of the least sensitive factor in the NPV calculation. This has a particular significance in that there are possibilities for further capital expenditures, especially for enhancing the efficiency of the process such as improving the liquid nitrogen usage and generating a finer mesh output (which commands premium prices). Allen and Biddulph (10) have also reported the relatively unimportant nature of the capital cost in their analysis of cryogrinding process.

The need for a better representation of the real market situation has stemmed from the sensitivity analysis in which only one variable is

flexed at a time. The investment simulation carried out, in which variables such as capital cost, output crumb price and variable costs are expressed in probability distributions, is capable of flexing all variables simultaneously. The use of probability distribution for a variable is an attempt to give a more realistic representation of the market, with the most likely outcomes commanding the highest probabilities.

The investment simulation performed for plant III, the most promising plant configuration, has shown that under the conditions described by the variable probability distributions (see Appendix I), the proposed investment has an expected NPV of about £5,800 with a standard deviation of £422,246 , and a 90% confidence interval of ± 0.4 %. The plant has a 62% chance of generating a positive NPV at 10% discount rate. Therefore, if the prescribed conditions prevail, this investment can be considered as economically feasible.

Although the result of the investment simulation points towards a marginally economically viable venture, however, there are several important economic and socio-environmental factors which must be taken into serious consideration. These unquantifiable, or not easily measurable, factors are not included in the economic analysis. In view of these economic and socio-environmental costs and benefits of recycling scrap rubber, State intervention will be most appropriate such as by making assistance, grant and/or subsidy available to the rubber recycling industry. The Dutch government has shown the initiative in this respect by extending assistance and cooperation to a rubber recycling company (Caruba Bv of Weert district, Netherlands), and has also passed an act of law forbidding the dumping and burning of scrap tyres from 1983 (Netherlands Waste Substances Act, 1979) (206).

The cash flows used in the investment appraisal techniques assumed constant costs, price and demand, and that these variables are independent of one another. Although the analyses performed are useful for comparing the relative performance of the plants and giving a very useful basis for studying the factors influencing the economy of the process, the postulated conditions are not fully representative of the real market situation. However, the causes and consequences of these assumptions on several important cost variables have been identified and can be discussed in some detail. The chart presented in Figure 8.1

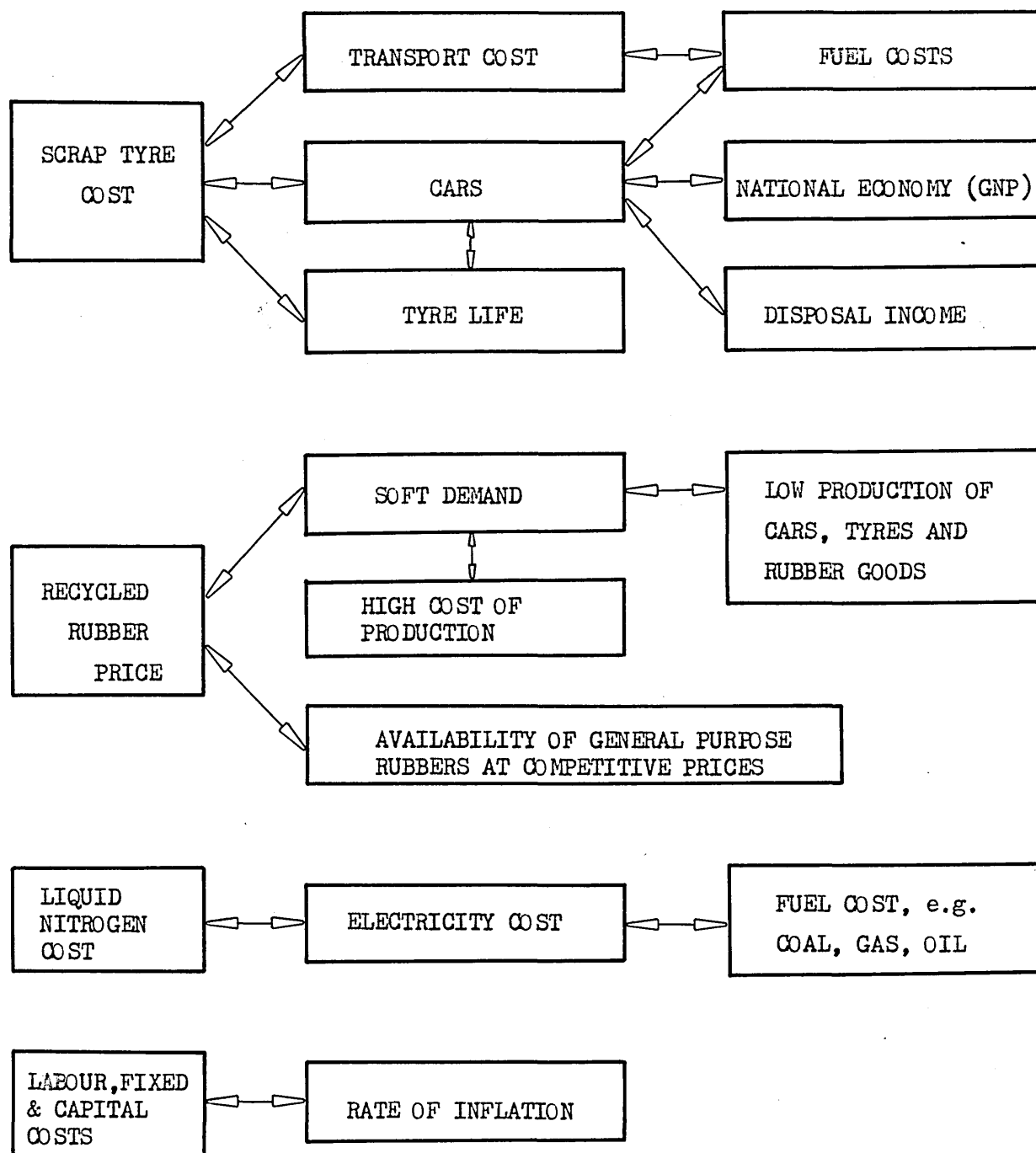
VARIABLESINFLUENCING FACTORS

FIGURE 8.1 Factors influencing the variable inputs of a cryogenic scrap rubber tyre grinding process.

shows these relationship.

(i) Scrap Tyre Cost : This depends on three main factors, namely the transport cost, the vehicle population and the tyre life. Transport cost affects the scrap tyre cost directly, as this represents almost the entire cost of scrap tyre input. Transport cost, in turn, depends on the fuel cost, transport labour costs and general vehicle maintenance overheads. The relationship between scrap tyres and the vehicle population and tyre life has been discussed earlier, and both of which have pointed towards a declining number of scrap tyre arising. This decreasing trend, in the long run, may cause scrap tyre cost to rise because of the additional effort and cost required to collect and transport the more widely scattered scrap tyres from location further away from the recycling plant.

(ii) Price of Recycled Rubber : The depressed price of crumb is due to soft demand, which may be related to the high cost of recycled rubber production, and the availability of general purpose virgin rubbers such as SBR at competitive prices. The soft demand has also been caused by the decreased tyre production, which consumed a high proportion of recycled rubber especially in tyre retreading, and the decrease in traditional recycled rubber markets such as carpet underlay and general mechanical rubber goods (eg. floor mats). The increasingly more stringent technical specifications for rubber products has also caused a considerable decrease in recycled rubber demand. The effect of the cost of rubber crumb production is discussed later. The current gross overcapacity of general purpose SBR, in relation to its demand, has forced the rubber producers to offer virgin rubber at competitive rates. This, together with the effect that recycled rubber has on physical properties through lack of understanding of the failure mechanism of the rubber vulcanizates incorporating recycled rubber, has encouraged rubber processors to use the relatively cheap virgin rubber instead of recycled rubber.

(iii) Cost of Liquid Nitrogen : This cost is closely related to the cost of its production, which is almost entirely the cost of electricity for the conversion of air to its liquid gas components. The electricity cost is, in turn, dependent upon fuel costs (coal and oil), and the Government's energy pricing policy. The costs of these limited energy resources have been increasing since the advent of oil price crisis

in 1973, and may be expected to continue to increase due to the increasing scarcity of these limited resources.

The cost of liquid nitrogen represents about three-quarters of the variable cost in rubber crumb production by the cryogrinding process considered. Hence, efficient usage of liquid nitrogen is of prime importance in determining if a cryogenic grinding system will achieve economic feasibility.

The potential for an improved liquid nitrogen usage in cryogrinding has been indicated by Vil'nits et al (168). Although the terms used are not clear, Vil'nits and coworkers have shown that the work to rupture (energy required to break-up the rubber pieces) during cryogrinding a vulcanized rubber passes through a minimum at a critical material temperature. This is shown schematically in Figure 8.2 where the criterion of comminution, which is a ratio of energy required for grinding a unit mass of the rubber to the newly generated surface area, is plotted against the temperature at which grinding is carried out. They give the relationship between the criterion of comminution, K, and the temperature of grinding, T, as

$$K = K_{\min} + \Delta K \left(\frac{T - T_o}{\Delta T} \right)^2 \left(3 - \frac{2(T - T_o)}{\Delta T} \right)$$

where K_{\min} is the minimum value of the criterion of comminution at the optimum temperature, T_o . The terms, ΔK and ΔT are shown in Figure 8.2. The optimum temperature for the vulcanized rubber sample they studied is in the range of -30° to -50° C. They also found that the optimum temperature increases when the speed of the hammer mill rotation is increased. Hence, it appears that this rubber may not need to be cooled to its embrittlement temperature for efficient cryogenic grinding, and therefore, a potential saving in the liquid nitrogen usage may be realised. A systematic investigation of the variables affecting the liquid nitrogen usage and cooling efficiency during the cooling of the rubber pieces will be necessary in order to establish optimum grinding conditions.

(iv) The Labour, Fixed Costs and Capital Cost can be assumed to increase in relation with the rate of inflation as measured by the Retail Price Index, which is in turn related to the state of the economy.

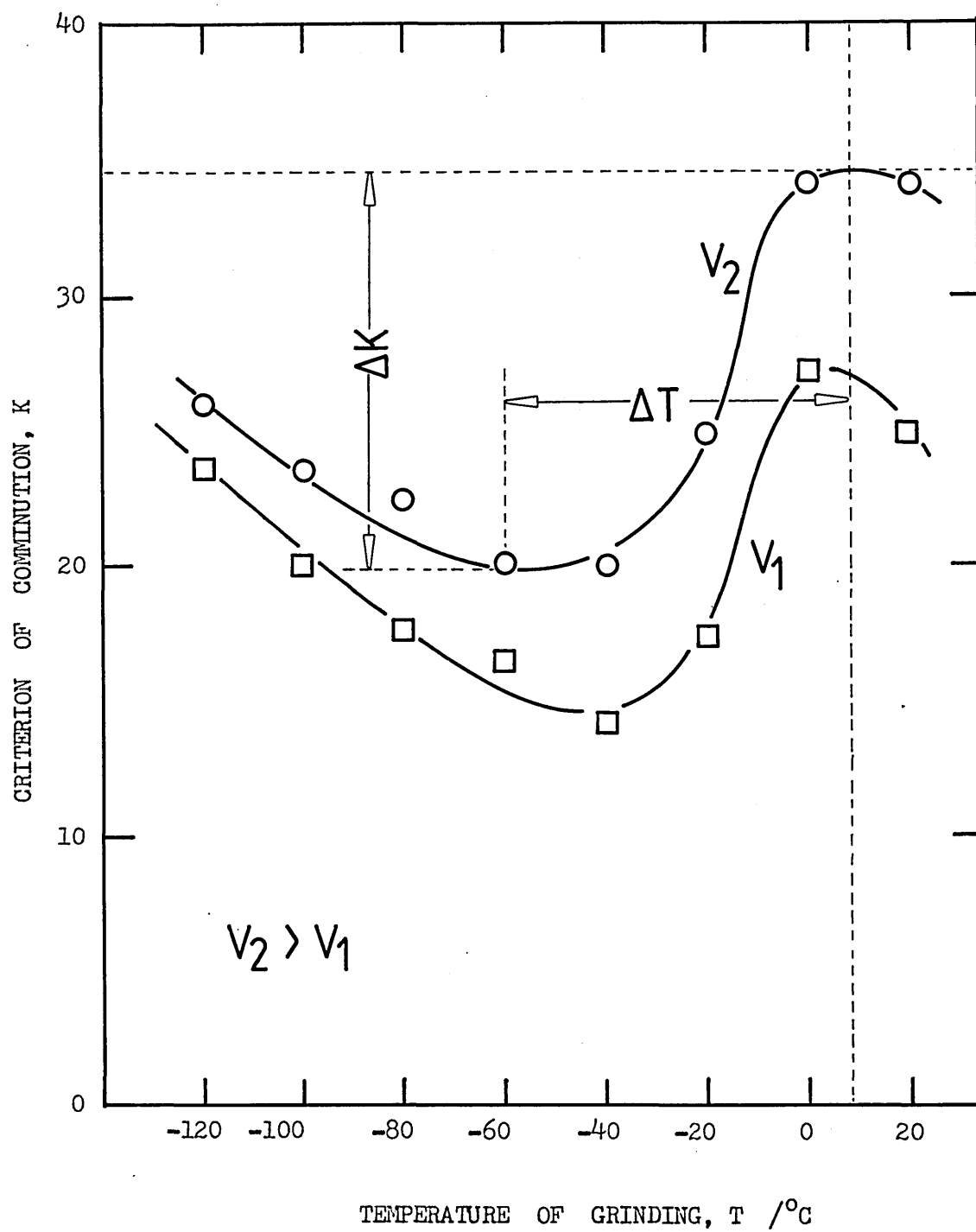


FIGURE 8.2 Variation of the criterion of comminution with grinding temperature. (from Vil'nits et al (168)).

The establishment of forecast models for these variables and the incorporation of these forecasts in the investment simulation model offer opportunity for further research work. The initial attempt to establish these forecasts has not been fruitful, however, it has indicated the need for a much more in-depth understanding of the factors influencing these variables, which requires a thorough going research programme.

8.3 Physical Properties Of Vulcanizates Incorporating Recycled Rubber

As rubber crumb is the product of the majority of the most promising rubber recycling processes, such as cryogenic grinding, ambient grinding and the Gould process, emphasis has been given to the influence of rubber crumb in the study of recycled rubber-rubber composites.

The results from our experimental investigations carried out with 40 mesh whole tyre crumb (WTC) - SBR and NR composites, together with the limited published data have enabled several important mechanisms governing the physical properties of these recycled rubber-rubber composite systems to be identified. These are discussed in some detail below.

a) Curing Agent Migration

The migration of curatives among different phases of a rubber-rubber composite is well-known (24,27,160,190-3). The majority of previous work were modelled with blends of two or more incompatible rubbers, or using planar models. In the present study, emphasis was given to the influence of particulated vulcanized recycled rubber in recycled rubber-rubber composites.

For constant cure conditions, the initial modulus and tensile strength of a recycled rubber-rubber composite changed with increasing volume fraction of recycled rubber incorporation. The change in the composite properties depends on the physical properties of the matrix and of the crumb. In general, where physical properties of the matrix were greater than that of the crumb the composite initial modulus and tensile strength decreased with recycled rubber incorporation. However, where the properties of the matrix were inferior to the crumb, such as our WTC-SBR system, the reverse is true. This change in physical properties with recycled rubber incorporation was observed by Swor et al,

and they found that with suitable adjustment in curative levels, they were able to partially retain the physical properties of the recycled rubber containing vulcanizate. They had attributed this behaviour to the migration of curing agent from the matrix to the recycled rubber particles. This was supported by the observation of Grebenkina et al and recent work on 40 mesh crumb-silicone rubber composites using a peroxide curing agent by Wilkinson (170).

The redistribution of sulphur in our WTC-SBR and WTC-NR composites has been studied using a Scanning Electron Microscope (in Chapter Six), and has generally provided further evidence of curative migration in particulate rubber-rubber composites. EDAX (Energy Dispersive Analysis of X-ray) techniques were employed in carrying out the direct measurement of sulphur curing agent in our recycled rubber-rubber composites. This curative migration study has found that the compounding variables which influence the degree of sulphur migration are : the amount of recycled rubber crumb; and the nature of the base and crumb rubbers. Together with studies carried out by other workers, our investigation has identified several factors influencing the redistribution of sulphur in a vulcanizate-rubber composite. They are : the relative solubilities of sulphur in the different rubbers; initial concentration of sulphur in the base mix; degree of unsaturation in the two phases; degree of crosslinking in the crumb particles; and time and temperature of the processing stages especially that of the mixing and vulcanization stages.

The curative migration process plays an important role in determining the properties of vulcanizates incorporating recycled rubber. Although present investigation has identified some factors influencing this process, such as sulphur contents, rubber unsaturation, and time and temperature of vulcanization, a thorough going scientific-technological investigation under controlled conditions is needed to elucidate the mechanisms involved.

b) Volume Fraction and Particle Size of Incorporated Rubber Crumb

The simple analysis carried out in Section 7.6 shows that high volume fractions of recycled rubber are needed to influence the cost of compounds which contain the recycled rubber. Hence, it is vital to investigate the effect on physical properties of vulcanizates incorporating recycled rubber, especially at high loadings.

The ultimate strength of the WTC-SBR and Trellfax's TCR-rubber composites have been shown to follow a modified form of the Simple Law of Mixtures (equation 5.5). However, for other composite systems, the relationship between the physical property and the amount of crumb incorporated is more complex.

One complication regarding recycled rubber loading is the way the volume fraction, ϕ_{RR} , of the rubber crumb is expressed, and it appears that the most appropriate form is to express the amount of recycled rubber as a percentage of its rubber hydrocarbon (RHC) to the total RHC in the composite.

Rubber crumb size is commonly specified with mesh size number eg. 40 mesh, which in effect is specifying that the rubber crumb has particle sizes of less than the openings of the mesh. Burgoyne et al (14) have shown that the smaller the particle size, the less the imparted physical property deterioration. The preliminary analysis performed in Section 5.2(b) based on Burgoyne's data has shown that for their rubber material systems, the strength ratio is inversely proportional to the square root of the sum of the effective diameter of the crumb and an inherent flaw size. Therefore, the commonly used method of crumb size classification is inadequate for a proper scientific description of the material system since there is usually a wide distribution of diameters within a specified mesh size. In addition, the proportion of each particle size in the distribution may not be the same. Figure 8.3 illustrates the possible size distributions for a crumb classified as 40 ASTM mesh size ($< 420 \mu\text{m}$). A scientific investigation of the influence of rubber crumb on the strength properties should, therefore use rubber crumb of narrow particle size distribution.

From the analysis using the Gent model (in Section 5.2(b)), it is clear that it is not necessary to grind the scrap rubber to sizes less than the inherent flaw size of the matrix rubber compound. This inherent flaw size is typically $20 \mu\text{m}$ for general purpose rubbers such as SBR and NR. This has a particular industrial significance in that although it is desirable to grind the scrap rubber to small mesh sizes (in order to avoid imparting excessive physical property deterioration to the composite, as well as to be able to command a premium price for the rubber crumb), there will not be any physical property enhancement

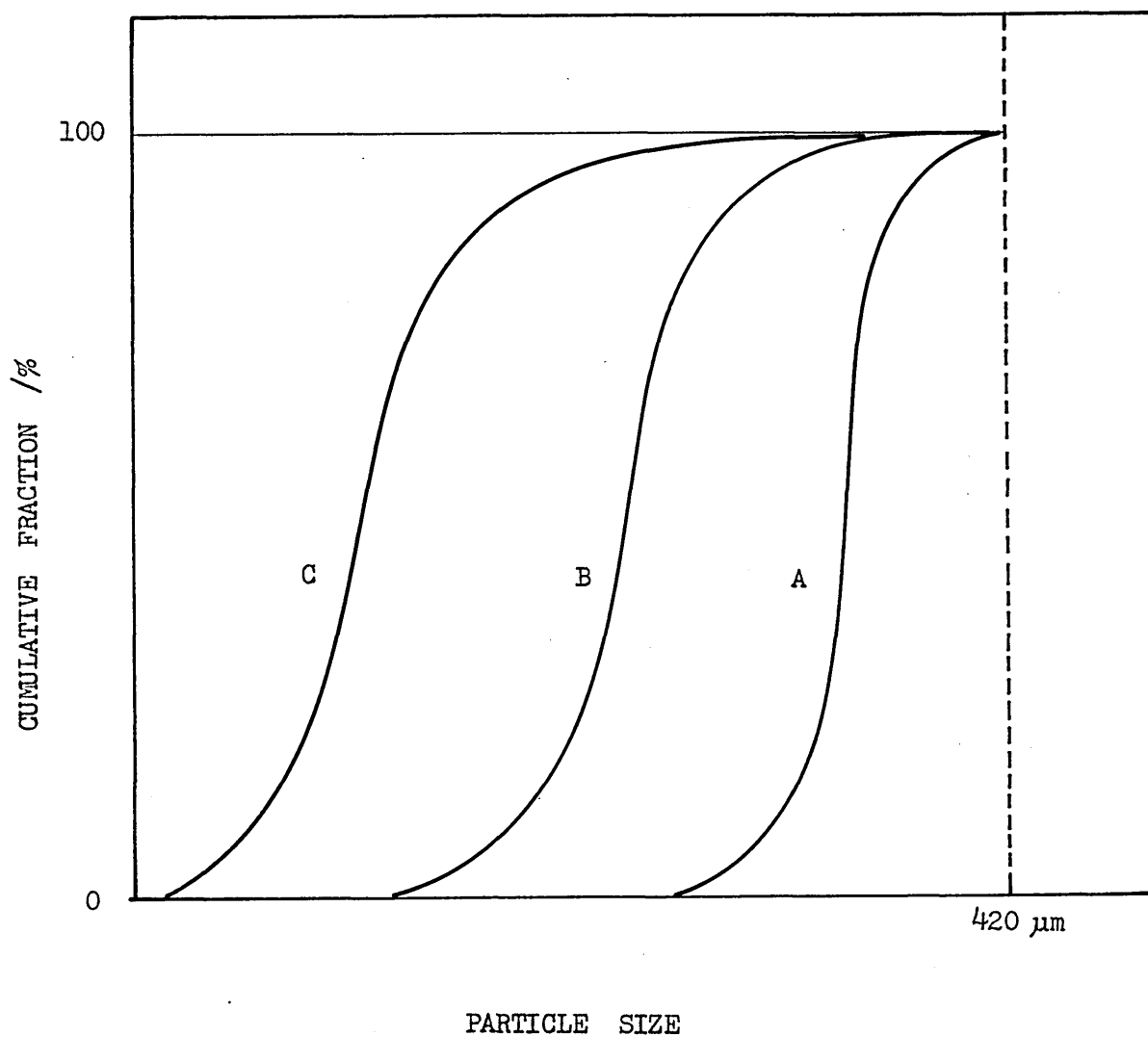


FIGURE 8.3 Possible particle size distributions for a crumb classified as 40 mesh (ASTM).

Curve A has a narrow size distribution in the 400 μm range;
Curve B has a wide size distribution; and Curve C has a size distribution narrowly distributed in the 100-200 μm range.

advantage to be gained in using crumb of sizes of less than 20 μm .

c) Coupling between Particles and Matrix

McNally et al (161) have attributed the reduction in ultimate properties of short fibre-thermoplastic composites to the effectiveness in which stress is transferred across the filler-matrix interface, which they termed Stress Transfer Interface. This concept may be applied to a recycled rubber-rubber composite where the interface concerned is between rubber particles and the rubber matrix, and the effectiveness of this interface is measured by the degree of bonding. This measure of the integrity of the bonding between the rubber particles and the matrix, R , is used in equation 5.5.

$$(\sigma_B)_C = R \phi_{RR} (\sigma_B)_{RR} + (1 - \phi_{RR}) (\sigma_B)_M$$

When applied to a TCR filled composite system, R is observed to be unity (refer Figure 5.14).

Two extreme situations may arise. (i) $R = 1$, indicating perfect bonding between the particle and the matrix. The surface of the Trellfax reclaim is reported (28) to have been partially devulcanized and this may promote adhesion between matrix and recycled rubber particle and facilitate the formation of strong interfacial bonds. However, the data of Figure 5.14 shows that $(\sigma_B)_{RR} < (\sigma_B)_M$ indicating that the Trellfax recycling process may have an adverse effect on the strength properties of the rubber crumb product. It would be interesting to examine how process parameters influence this property degradation.

(ii) $R = 0$, indicating zero bonding. Although this situation is unlikely to occur in commercial material system, it is interesting from a scientific point of view, since it removes one term from the right hand side of equation 5.5. This will facilitate the interpretation of physical property data.

In the WTC-SBR composite systems, which also behave according to equation 5.5, and in practical systems, the stress transfer parameter, R , takes a value between zero and unity. It is desirable to make R as large as possible in order to optimise the strength properties of a recycled rubber-rubber composite. One possible way of achieving higher

R, by promoting bonding between the matrix and the crumb particles, is to treat the particle surfaces. TCR crumb has been given a surface treatment (termed 'cold devulcanization' by the manufacturer) to promote bonding. A coupling agent may also be used. Investigation into this area represents an opportunity for further research.

d) Stress - Strain Relationship

The network mechanics of recycled rubber incorporated vulcanizates has not been studied previously. In this work, the mechanics of our WTC-rubber composites have been investigated using the stress-strain behaviours of these composites. The WTC-SBR and WTC-NR composite systems exhibit a general stress-strain relationship similar to that of a conventional elastomeric network, showing Gaussian and non-Gaussian regions, debonding between matrix and filler particles, and strain crystallisation for the strain-crystallisable NR system. Two commonly used models have been employed to study the network behaviours. The Mooney-Rivlin model has been used for low extension Gaussian behaviour, and a non-Gaussian model based on a simplified form of the inverse Langevin function has been used for the high extensions.

The WTC-SBR composites showed deviations from the Mooney-Rivlin plots and the non-Gaussian plots at high extensions. These were attributed to the onset of the debonding process. At low sulphur levels of between 1 - 2 phr, a critical strain for debonding, λ_K , can be obtained from both the Mooney-Rivlin and non-Gaussian plots. For $\lambda < \lambda_K$, the material system behave like conventional elastomeric networks exhibiting Gaussian and non-Gaussian type behaviours. At $\lambda \geq \lambda_K$, debonding the matrix and particles takes place, and the material systems exhibit a curvilinear non-Gaussian behaviour. At high sulphur loading, the WTC-SBR composites are found to have λ_K lower than the breaking strain.

The network parameters from the Mooney-Rivlin plots i.e. the Mooney constants C_1 and C_2 , for these recycled rubber-rubber composite systems are not fully understood. It has been reported (204) that C_2 may be related to the hysteresis of the rubber network. This association of C_2 and hysteresis is thought to have given rise to the peculiar low strain stress-strain behaviours for the WTC-SBR composites at low sulphur levels. Compounds prepared from rubber crumb have been reported (205)

to show excellent hysteresis and damping properties. The commercial potential for high hysteresis and high damping materials is bright especially in the fields of sound and vibration insulation applications, however due to lack of data, this line of study has not been followed. This has also indicated the need to investigate C_1 and C_2 in greater detail.

The study of stress-strain relationship of these material systems has led to a discussion of possible failure mechanisms. It is proposed that two mechanisms may have been involved (see Section 5.4), however there is insufficient evidence to fully support this proposal. The failure mechanisms can be classified into cohesive and adhesive failures. In the former, failure initiates from within the matrix some distance away from the stress transfer interface, while in the latter, the failure initialisation originates from the adhesive or stress transfer interface region. In the case of adhesive failure, modification of the stress transfer interface may improve the ultimate strength properties. This may be achieved through surface treatment of the recycled rubber particles as described in (c). The modification of the curing system may also improve strength properties through the elimination of curative migration and curative depleted regions at the interface. In depth microscopic investigations to establish the failure mechanisms, such as shown by the electron photomicrographs in Figure 8.4, represent further research opportunity.



FIGURE 8.4 Photomicrograph of a fracture surface of a recycled rubber-rubber composite.

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SURVEY OF RUBBER RECYCLING FACILITIES IN EUROPE AND NORTH AMERICA

A.1 Purpose

The main objectives of this survey are

- i) to obtain up-to-date information regarding rubber recycling facilities currently in operation;
- ii) to obtain information regarding the rubber recycling technologies employed, and estimates of cost data (capital, fixed and variable costs).

A.2 Geographical Regions Covered

As pointed out elsewhere in this report, there is only one rubber recycling facility currently in operation in the UK. This has posed severe limitations on the study, and made the collection of cost data, especially operating costs, extremely difficult. Together with the severe economic situation of the manufacturing industry as a whole and rubber processing sector in particular, it became necessary to extend the geographical boundary further afield.

The regions covered by this survey include the United States of America, West Germany, the Netherlands, Belgium, Denmark, Norway, France, Sweden and Switzerland.

A.3 Selection of Companies Involved in Recycling Rubber

Given the wide geographical area covered, the most convenient source of information of the recycled rubber producers is trade/business directories. Kompass (173), with worldwide editions, has been used to obtain details of the firms involved in recycled rubber. A large number of companies were listed under the general heading of Reclaimed/Regenerated Rubber Producer/Distributor. The majority of these companies were not actually involved in manufacturing, but were distributors or agents for recycled rubber (this is due to the nature of the business directory). A total of 55 firms were selected, which is all the firms listed as manufacturers of recycled rubber (recycled rubber includes a large group of products such as reclaimed rubber, tyre tread grindings, inner tube reclaims, rubber crumb and mechanical rubber reclaims). The breakdown of the 55 firms by their countries is

given below:

<u>Country</u>	<u>No. of Firms</u>
U.S.A.	19
Germany	3
Netherlands	4
Belgium	3
Denmark	4
Norway	3
France	10
Sweden	5
Switzerland	4
	<hr/> 55 <hr/>

A.4 Questionnaire Design

The questionnaire has been designed to achieve the objectives set, albeit with skepticism regarding the response to cost data enquires. The survey questions were prepared in the self-completion form, avoiding open-ended questions as far as practicable. Simple alternative and multichoice questions were used whenever possible. Care has been taken to provide sufficient scope for respondents to make valid answers to the multichoice questions.

The questions were grouped in topics as shown below:

<u>Question No.</u>	<u>Aim</u>
Q1 and Q2	to identify the technology and process employed;
Q3 and Q4	to identify the source and type of input into the process;
Q5	to gather estimates of capital cost, and output capacity;
Q6	to establish expected life of plant and annual cost of maintenance;
Q7	to collect operating costs;
Q8	to gather information on types of output and their retail sales prices.

A copy of the questionnaire is presented at the end of this Appendix.

The questionnaire has been translated into German and French to encourage response.

A.5 Questionnaire Administration

The self-completion questionnaire, together with a cover letter were sent to the informant firms by post. The cover letter has three main functions: (i) declaring the neutrality of this study by emphasising the sponsoring body; (ii) stating the need for the survey; and (iii) offering assurance on the confidentiality of the data provided. A copy of the cover letter and questionnaire are enclosed at the end of this Appendix. The questionnaire was administered in April/May 1981.

A.6 Result and Discussion

Response to the questionnaire was predictably low. A total of 14 responses were received, giving a response rate of 25%. Details of the responses are given below:

<u>Country</u>	<u>No. of Firms</u>	<u>Positive Response</u>	<u>Negative Response</u>	<u>Total</u>
U.S.A.	19	2	2	5
Germany	3	1	1	2
Netherland	4	1	1	2
Belgium	3	0	0	0
Denmark	4	0	0	0
Norway	3	0	0	0
France	10	0	2	2
Sweden	5	0	1	1
Switzerland	4	1	1	2
Total	55	5	9	(25%) 14

Several factors may have caused such low response . As evidenced from the entries of the UK edition, Kompass directories included a large number of distributors in their list of manufacturers. (Kompass does not explicitly indicate a manufacturer, rather it groups manufacturers and direct provider of a service together). Therefore, similar classifications may be expected from other editions. This could have resulted in a large number of questionnaire being sent to distributors/agents, and hence a relatively higher negative response received.

The questionnaire involves the disclosure of some costing data which

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may have acted as a deterrent to response. This may be particularly true with the newly formed firms, such as Trelleborg of Sweden. Furthermore, the questionnaire requires the involvement of both technical and costing personnel. Hence, response to the questionnaire requires the cooperation of both, and sometimes several departments in the firm, failure of one of the departments to cooperate will result in a non-response.

The non-response from Denmark, Norway and Belgium may be partly due to the questionnaire being presented in a different language. A rubber recycling facility is usually a small operation, employing less than 25 personnel, hence the lack of suitable personnel to deal with the foreign language questionnaire may have caused the non-response.

From the table, it is seen that the number of negative response is higher than the number of positive response. (A positive response is one which the informant firm has answered, at least partially, the questionnaire. A negative response is one in which the questionnaire has not been answered, or the informant firm is not, or no longer, a recycled rubber manufacturer.) Six out of the nine negative responses did not produce recycled rubber, two had ceased production (in 1970 and 1975), and one rubber recycler had returned a negative response on the grounds of its special situation.

Three out of five positive respondents employed conventional processes i.e. digester, pan heater and reclaimator processes, which cannot handle steel belted tyres without incurring additional costs. The other two respondents produced rubber crumb, one using the cryogenic grinding process, the other a mechanical grinding process.

Scrap tyres were the main source of input, however, some processes required the whole tyres to be broken down, and with metal and fabric removed. Tyre buffings, factory scrap rubber and inner tubes were used by some processors. The main suppliers of the input were scrap merchants, tyre retreaders and municipal disposal units.

The maximum product output capacity was between one and five tonnes per hour. The two crumb producers both had a two tonne product per hour facility. The normal operating output range was between 70% to 100%,

with majority of the firms surveyed having a range of 70% - 90%. The total capital cost for recycling machinery ranged from about £500,000 to £1.5 million (converted from foreign currencies, conversion rates used were averages of May/June 1981. £1 equivalent: DM4.72; US\$2.00; Dutch G5.24; Swiss FR4.12).

Response to Q6 was incomplete, generally, the expected^{life} of the main machinery was between 15 to 20 years. The expected life of a hammer mill used in the cryogenic grinding process was 5 years. The response to operating cost enquiries was scarce and incomplete, and in ambiguous terms (eg. cost per day), thus making it useless.

A wide range of output was produced by the rubber recycling firms surveyed. The products included whole tyre reclaim (priced between £230 to £270 per tonne), butyl reclaim (priced about £370 per tonne), and rubber crumb of various sizes (0 - 0.5mm priced about £130 per tonne; 10 mesh priced about £130 per tonne and 30 mesh priced about £165 per tonne). All prices were converted from foreign currencies.

A.7 Conclusion

The survey has succeeded in supplementing recent published information regarding rubber recycling facilities currently in operation in Western Europe and the United States of America. It has also supplied information regarding the type of rubber recycling technologies currently being employed, and some indications of the capital and operating costs for some of these recycling facilities, albeit in different currencies. Including one in the UK and Sweden, there are altogether five rubber recyclers in Europe.

A large number of rubber reclaimers (mainly employing high energy consuming processes such as heater pan and digester processes) had ceased production in early and mid 1970's as direct result of high energy costs and low demand. Two of the respondents to the survey were examples.

The older technologies, such as the digester and reclaimator, have been improved so as to be able to handle steel belted tyres, although with an additional cost.

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The usefulness of the survey has been hampered by the low response rate, and the failure of some known rubber recyclers to respond to the questionnaire. The differences in currencies and economy conditions from the UK system meant that the cost data and prices may not be used as a comparison with a similar set-up in the UK.

Pond Street
Sheffield S1 1WB
Telephone Sheffield 20911 (STD Code 0742)
Telex 54680

Department of Applied Physics
Head of Department D. A. Davies B Sc PhD FInstP

Our Ref SGT/AH

Dear Sir

RUBBER RECYCLING INDUSTRY

I am a Research Assistant at Sheffield City Polytechnic engaged in a research project involving the technical and economical study of scrap rubber recycling methods. This project is sponsored by the Sheffield Local Education Authority.

In tackling this complex problem I wish, ultimately, to establish the most cost efficient way of recycling scrap rubber into the most technically acceptable product.

I have so far surveyed the various rubber recycling processes by means of a comprehensive search of published literature. However, the cost and technical data obtainable from this source is not always sufficiently detailed or up-to-date. Any assistance from the rubber recycling industry is, therefore, most valuable.

In the United Kingdom I am faced with the problem that there is only a limited number of rubber recycling facilities in current operation. The data I can obtain is, therefore, very limited. In order that I might obtain sufficient factual operating data I sincerely request your kind assistance. I shall be most grateful if you could furnish me with the information I request.

I understand that some information may be classified as sensitive; however you can be assured of the confidentiality in handling all the information and data. You will have free access to the project report to ensure that there is no infringement of secrecy.

In view of the importance of the recycling of the limited natural resources and the ultimate survival of the rubber recycling industry, your assistance will be very much appreciated. I shall be most happy to learn of any additional co-operation that you may be able to offer.

Thanking you in anticipation of your co-operation and, if the project is of interest to you, I shall be most delighted to make available my findings.

Yours faithfully

S G Tong
Research Assistant, Polymer Science & Technology Research Group

1. What type(s) of rubber recycling process do you use at present?
Please tick in the appropriate place(s) below:

Digester Process	.....
Recalimator Process	.....
Cryogenic Grinding	.....
Pyrolysis	.....
Depolymerised Scrap (Solution) Process	.....
Others	.....

If others, please give a brief description of the process below

2. Does your process have any special characteristics as compared with a normal process of a similar type?

Yes	.....
No	.....

If Yes, please point out the special characteristics below

3. What is the type and form of the input into your process?

Whole tyre	.....
Shredded tyre	.....
Metal-free Shredded Tyre	.....
Metal and Fabric-free Ground Tyre	.....
Tyre Buffing	.....
Inner Tube	.....
Vulcanised Scrap Rubber from Rubber Processors	.....
Others	.....

If others, please state below

Can steel-belted types be handled without incurring additional preparatory costs?

Yes	.....
No	.....

4. What is your main source(s) of input?

Tyre Depots/Distributors	.....
Tyre Retreading Plants	.....
Rubber Processors	.....
Scrap Merchants	.....
Municipal Disposal Units	.....
Others	.....

If others, please state below

5. What are the type(s) of machinery used?

Please tick in the appropriate place(s) for the MAIN machine(s)

Grinder, Hammer Mill or any Pulveriser	.....
Freezing Tunnel	.....
Reclaiming Vessel, Autoclave or Any Reaction Vessels.....	.....
Extruder-type Reaction Machine	.....
Internal Mixer-Type Reaction Machine	.....
Pyrolytic Retort	.....
Others	.....

If your answer includes Others, please give the Others main machine(s)

What is the total capital cost for the recycling MACHINERY?
(Please exclude land, buildings, etc.)

.....

What is the total capital cost for the recycling FACILITY?

.....

What is the maximum output of the recycling facility?

.....tonnes/tons/kg/Ib⁺ of product
per HOUR

⁺(please delete as appropriate)

5. (cont)

What is the normal operating range?

40 - 50% of maximum output	.....
50 - 60% of maximum output	.....
60 - 70% of maximum output	.....
70 - 80% of maximum output	.....
80 - 90% of maximum output	.....
90 -100% of maximum output	.....

6. What is the expected life span of the main machine?

..... Years

Is there any part(s) that require(s) frequent replacement?

Yes

No

If Yes, how frequent is the replacement?

..... Years/Operating Hours/⁺

⁺(Please delete or fill in as appropriate)

What is the total cost of replacement?

.....

7. What are the operating costs of your recycling facility?

£

Material Input

e.g. scrap tyres, tyre buffing, etc.	Per hour/Day/Kg of scrap rubber
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Other Materials Input

e.g. reclaiming agents, liquid nitrogen, etc.	Per hour/Day/Kg of scrap rubber
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Energy Consumption

e.g. gas fuel, electricity	Per hour/Day/Kg of scrap rubber
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(Please delete or fill in as appropriate)

8. What are the types of recycled/regenerated rubber manufactured?
What are their retail prices?

		Price Per Kilo
Whole Tyre Reclaim
Butyl Recalim
Rubber Crumb (Please state size).....		
Size:

Others

If others is one of your answers, please state the recycled rubber you manufactured below

<u>Type of Recycled Rubber</u>	<u>Retail Price per Kilo</u>
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DETAILS OF COMMERCIALY AVAILABLE RUBBER RECYCLING PROCESSES

This appendix gives details of some of the rubber recycling processes that are employed commercially. Other processes are available or have been employed previously but doubts concerning their commercial viability preclude them from this discussion.

B.1 Conventional Processes

(a) The Digester Process

The Digester process originates from the alkali process, which was developed by Authur H. Marks in 1899 (46,70). Several improvements have been made since, and a modern digester can handle 2500 kg to 3000 kg of scrap rubber per batch (1,51).

Figure B.1 shows a flow diagram of the digester process. The scrap rubber, typically of scrap vehicle tyre, is first cracked or broken down with a cracker mill, from which large metallic components such as tyre bead wires can be separated. The cracked stock is passed over a vibrating screen, the overs are returned to the cracker whilst the bottoms are passed through a series of magnetic separators removing any remaining traces of ferrous metal. The metal-free particulate scrap rubber, 6 to 10 mm in effective diameter and containing all of the organic fibres, is stored in readiness for digestion.

The digester is a large jacketed autoclave with a rotating shaft. A series of paddles is spaced along the shaft which when rotated creates a turbulence mixing action. Weighted particulate scrap rubber is mixed with definite proportions of water, reclaiming and defibring agents prior to loading into the digester. Typical reclaim formulae for reclaiming Scrap black natural rubber tyre tubes, and whole passenger car tyres are shown in Table B.1 and B.2 (65). Super heated steam is introduced into both the jacket and the vessel to obtain digestion temperature of between 170° - 225°C (equivalent to 1.4 - 2.4 MPa of steam pressure). The paddled shaft is in continuous motion to ensure uniform penetration of heat and chemicals. The reaction time is between 5 to 10 hours.

Pressure and heat alone are sufficient to devulcanise natural rubber,

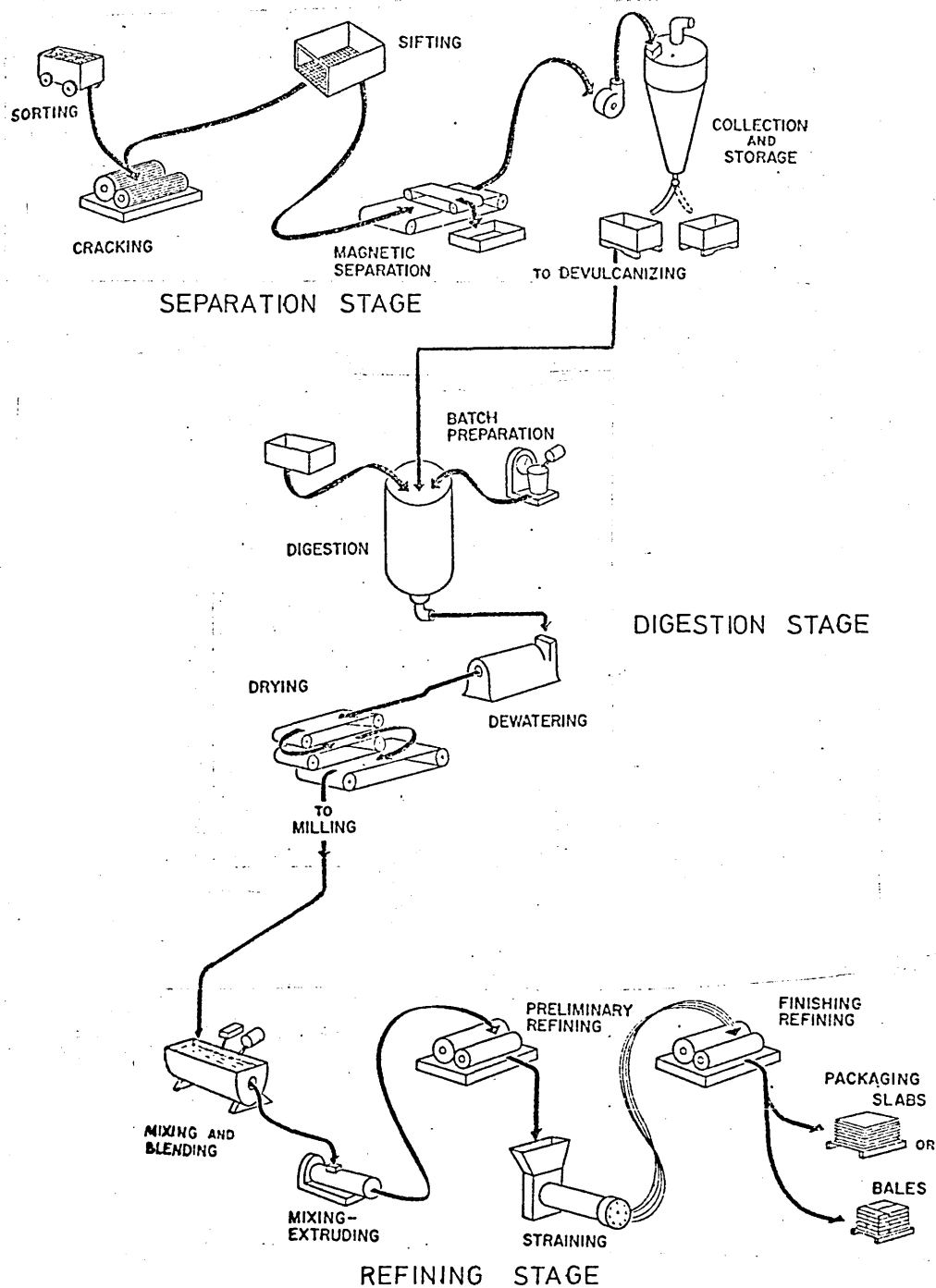


FIGURE B.1 Schematic Flow Diagram of the Digester Process
(from Vanderbilt (71))

Table B.1 Typical Natural Rubber Reclaim Formula

<u>INGREDIENT</u>	<u>PARTS</u>
NR Crumb (6 mm, black)	100
Tarene	3
Whiting	10
Liquid Caustic (30% NaOH Solution)	2
Water	2
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Reaction Time	5 hours
Steam Pressure	1.03 MPa
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Table B.2 Typical Whole Tyre (Passenger) Reclaim Formula

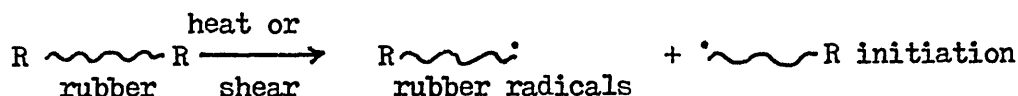
<u>INGREDIENT</u>	<u>PARTS</u>
Whole Tyre Crumb (metal-free, 1 mm)	100,00
Paraflux	5.40
OXCO	6.00
Solvenol	2.00
Pitt Consol 500	2.00
300° Mineral Rubber	1.70
Carbon Black IFAH	4.00
Resoncinol	0.06
Triton X 100	0.06
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Reaction Time	5 hours
Steam Pressure	1.03 MPa
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the addition of sodium hydroxide solution aids in improving the efficiency as well as hydrolysing most of the organic fibre (if fibre is present). Styrene Butadiene Rubber (SBR) compounds harden on heating, so that reclaiming agents are needed with this material. Tyre rubber compounds consists of both natural rubber and a few synthetic rubber such as SBR, butyl rubber and polybutadiene rubber. Similar trend of mixing the different types of rubber can be found throughout the rubber industry especially in hoses, beltings and rubber shoes. A reclaiming agent should therefore be able to devulcanise SBR whilst not imparting too much degradation to the natural rubber component. Reclaiming agents of such capability have been developed and can be divided into four categories, namely, phenol alkyl sulphides and disulphides, aliphatic and aromatic mercaptans, amino compounds, and unsaturated compounds.

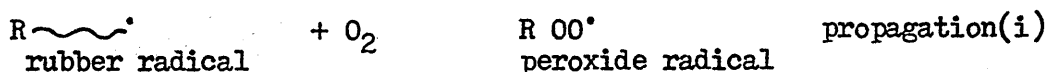
The phenol sulphides/disulphides group is the most effective and is widely used commercially. A recent report (4) suggests that the effectiveness of reclaiming as measured by the Mooney Viscosity can be improved by chlorination. This group is particularly active with sulphur-cured vulcanizates in the presence of oxygen (1). The mercaptans group is less effective and presents a problem of odour. The aromatic mercaptans are more effective than the aliphatics. The amino compounds are very effective and can be used in conjunction with caustic soda, which digests organic fibres and results in an alkali reclaim. Amino reclaiming agents are more effective in reclaiming non-sulphur cured vulcanizates, but they inherently induce staining in the reclaim produced. The effectiveness of amino compounds in descending order is primary amines, secondary amines and tertiary amines. The unsaturated compounds are the oldest reclaiming agents used. They mostly consist of unsaturated organic oils and solvents having a complex chemical composition and mostly derive from the heavy fraction of crude oil cracking plants and from natural resins. Terpene, coal tar naphtha, indene, dicyclopentadiene are some examples. The effectiveness is largely dependent on the degree of unsaturation (1).

Thermo-mechanical rubber reclaiming, as in the case of the digester process, is believed to follow a radical mechanism (1,46). The presence of softeners and plasticisers assist in loosening the closed vulcanized rubber network through swelling, thus enabling reclaiming

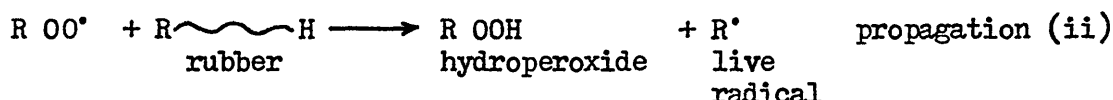
agents to penetrate uniformly into the rubber network. On heating and mechanical shearing (as in refining mills), rubber molecules, vulcanized or otherwise, break down and form radicals:



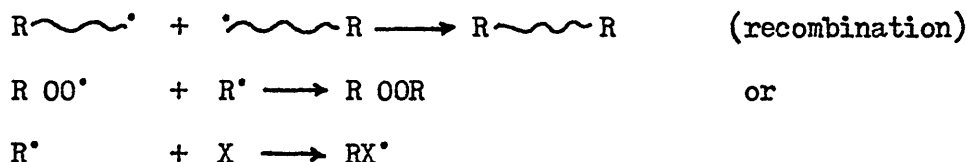
where R represents a rubber chain or a network. Oxygen accelerates the process of breakdown (1, 7, 8, 9, 46) by peroxide radical formation:



and the subsequent hydrogen abstraction from another chain or network, forming a hydroperoxide completing the scission, and another live radical:



The reaction may be terminated by combination:



where X represents the reclaiming agent.

The role of reclaiming agents is to promote the scissions, which could occur at the crosslinks or molecular chains (1, 28, 46), through peroxide radical formation and the formation of a more stable radical $\text{RX} \cdot$. The exact reaction mechanism is not known and is expected to be more complex than that described briefly above (1, 46).

The digested product is blown out of the reaction vessel and washed. Water is removed in a de-watering press, and the de-watered product is conveyed to a hot air dryer which evaporates the excess moisture. The dried digested rubber is mixed with small quantities (3 - 4 parts) of reinforcing filler (such as GPF black) and processing agent, and then passed through a close-nip (0.025 mm) refining mill. The preliminary

refined reclaim is fed into a strainer which removes any non-magnetic metal and other foreign matters such as stone and glass. The strained product is further refined by a series of very tight-nip (0.013 mm) mills, and removing any vulcanized hard rubber particles. The refined reclaimed rubber is removed continuously from the refining mills and plied into slabs and baled.

(b) The Reclaimator Process (5, 72)

This continuous process was patented by the US Rubber Reclaiming Co in 1946 and was granted US Patent 2 653 348 and 2 653 349 (128, 129). The process takes its name from the reclaiming vessel i.e. the Reclaimator machine.

The Reclaimator is essentially a heavy duty screw extrusion type machine. Metal and fabric-free fine rubber crumb of 30 mesh previously mixed with oil and reclaiming agents is automatically fed at a predetermined rate into the hopper which is situated at one end of the Reclaimator. The elevated temperature of about 200°C, is generated through mechanical work of friction between the rubber particles, the screw and the machine cylinder walls. The success of reclaim rubber production using this process rests on the initial rapid softening of vulcanized rubber when heated. Figure B.2 traces the plasticity of a vulcanized rubber on the time of heating.

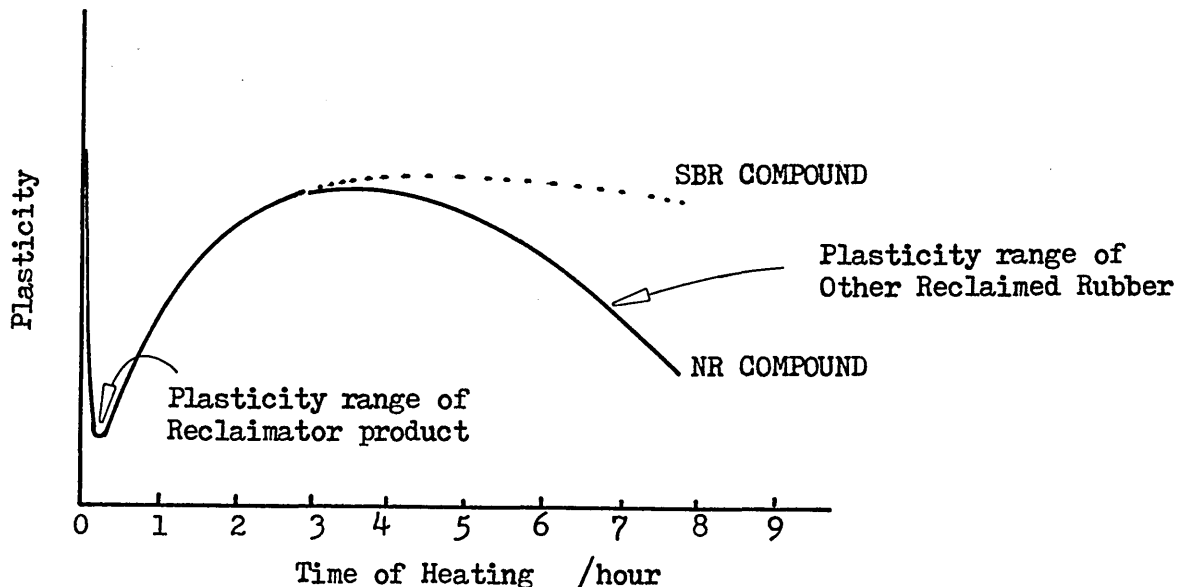


FIGURE B.2 PLASTICITY OF RUBBER VS TIME OF HEATING

Figure B.3 shows schematically the Reclaimator process. The separation stage is similar to that employed by the Digester process, except that the Reclaimator does not digest organic fibres, does not tolerate metallic contamination and requires finer crumb. Hence a more elaborate procedure is required to obtain the desirable rubber crumb. The predominantly metal-free cracked stock is passed over a series of scalping screens where three distinct fractions are obtained, namely the bottoms rubber-rich fraction, the light fabric-rich fraction, and the heavy oversize. The bottoms consist of mainly fine rubber particles and are conveyed to a classifying screen and subsequently to the grinding mills. The heavy oversize is conveyed to a primary hammer mill reducing its size and returning it to the scalping screens. The fabric-rich fraction is treated in a series of hammer mills, followed by reel beaters and air flotation tables removing the fabric components from the rubber. The rubber component is passed on to the grinding stage where it is being ground to 30 mesh fine crumb. Pneumatic conveying system is used to transport the crumb and magnets are strategically located throughout the separating and grinding stages to remove any remaining traces of metal. The metal-free, fabric-free fine rubber crumb is stored in readiness for reclaiming.

The rubber crumb, oil and reclaiming agents are individually metered and blended in a continuous pug mill prior to entering the feed hopper of the Reclaimator. In the Reclaimator, the mixture is subjected to heat and pressure. The residence time at 200°C is about 5 minutes during which the fine rubber crumb is devulcanised. As the reclaim is discharged from the Reclaimator, it is cooled by fine sprays of water, and then mixed with required amounts of reinforcing or inert fillers in a mixing extruder. The extruded stock is cut into small pieces with a rotary knife fitted at the extruder head. These are then conveyed to the refining section.

The refining operation is much the same as that used in the Digester process in that the reclaimed rubber is preliminarily refined, strained and refined, and finally formed into slabs or baled. Pelleted forms of reclaimed rubber are also available.

B.2 Size Reduction Processes

(a) Cryogenic Grinding - The Air Products Process

This cryogenic grinding process is developed and marketed by Air Products and Chemicals Inc (USA). The process is based on US Patent

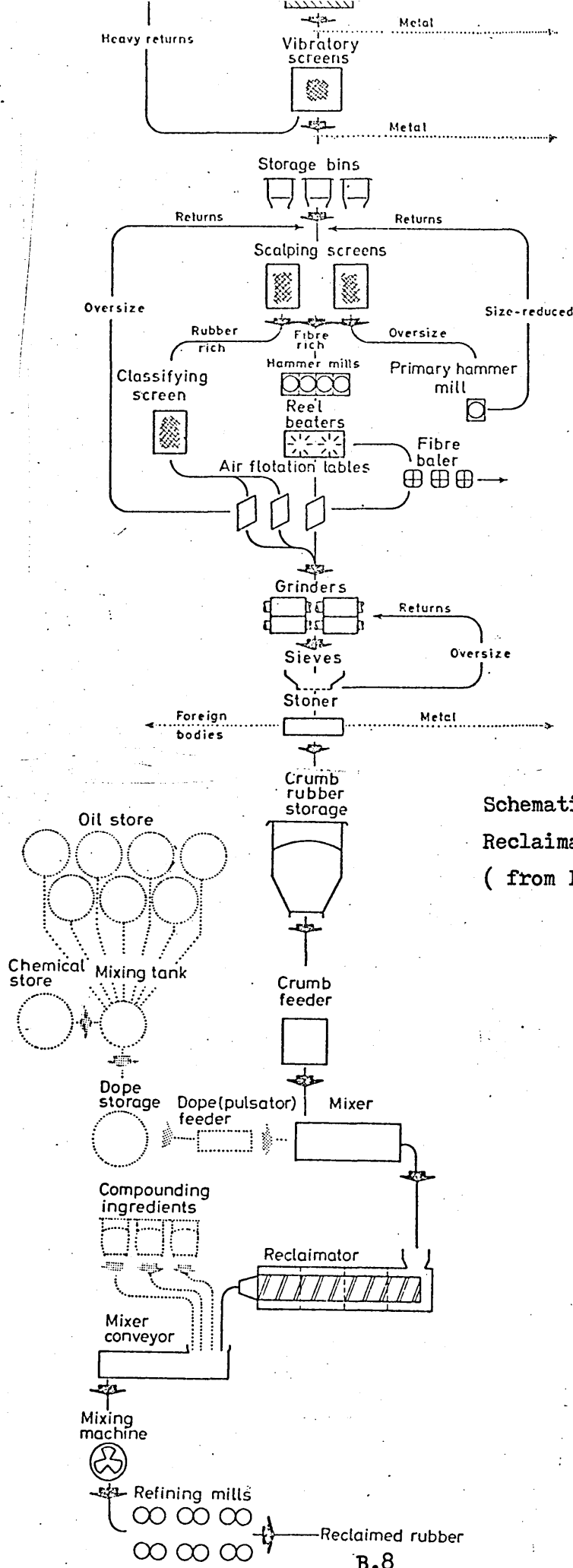


FIGURE B.3
Schematic Flow Diagram of the
Reclaimator Process
(from Blow (72))

4 025 990 (1977) (111). This is by far the most successful scrap rubber cryogenic grinding process. Winson BV of Maarheege, Netherlands, and George H Hughes Ltd of Birmingham, England, are two of the four European operators based on this process.

Figure B.4 shows the schematic diagram of the basic system as described in US Patent 4 025 990 (111). The Air Products process can be considered as a complete system in the sense that the process starts from the most fundamental raw material, whole scrap tyres in this case, and converts it into a product, fine rubber crumbs in this case.

The process can be looked upon as the cracking, separating and grinding stages of a whole tyre recalining process. However, the product of these ambient operations has both the technological and economic limitations. The high proportion of overs in the screening process, about 95% (5), means that rubber particles have to spend more time in the grinding mill, and, as a result, the heat build-up in the particles is considerable, temperatures of 100°C to 110°C are common, and will inevitably induce degradation of the rubber. The higher the proportion of rubber particles returning to the grinding mill, the smaller will be the throughput, and consequently the higher the energy consumption. Cryogenic grinding offers the possibility of overcoming these problems, at least the technical ones, by cooling the scrap rubber to or below its glass transition or embrittlement temperature, which is about -80°C. (The glass transition temperature of gum rubber vulcanizate, i.e. cured rubber without the addition of organic or inorganic fillers, is between -80°C to -100°C.) Rubber at this temperature becomes brittle and can therefore be pulverised easily, consequently the problem of heat degradation is eliminated.

In the Air Products' process, whole tyre is shredded into pieces of size 50 mm to 150 mm, passing over a vibrating screen to remove part of the dirt and water, and then to a cryogenic freezer. The tyre pieces are cooled to a temperature of about -100°C on leaving the freezer. A hammer mill pulverises and liberates the embrittled rubber from the reinforcing components of the tyre (i.e. steel beads and belt, and fabric cords. Rubber particles of less than 20 mm are generated. The steel and fabric members are less than 50 mm long (probably due to the shredding operation).

The first of these is the fact that the majority of the population of the United States is of European descent, and that the majority of the population of the United States is of European descent, and that the majority of the population of the United States is of European descent.

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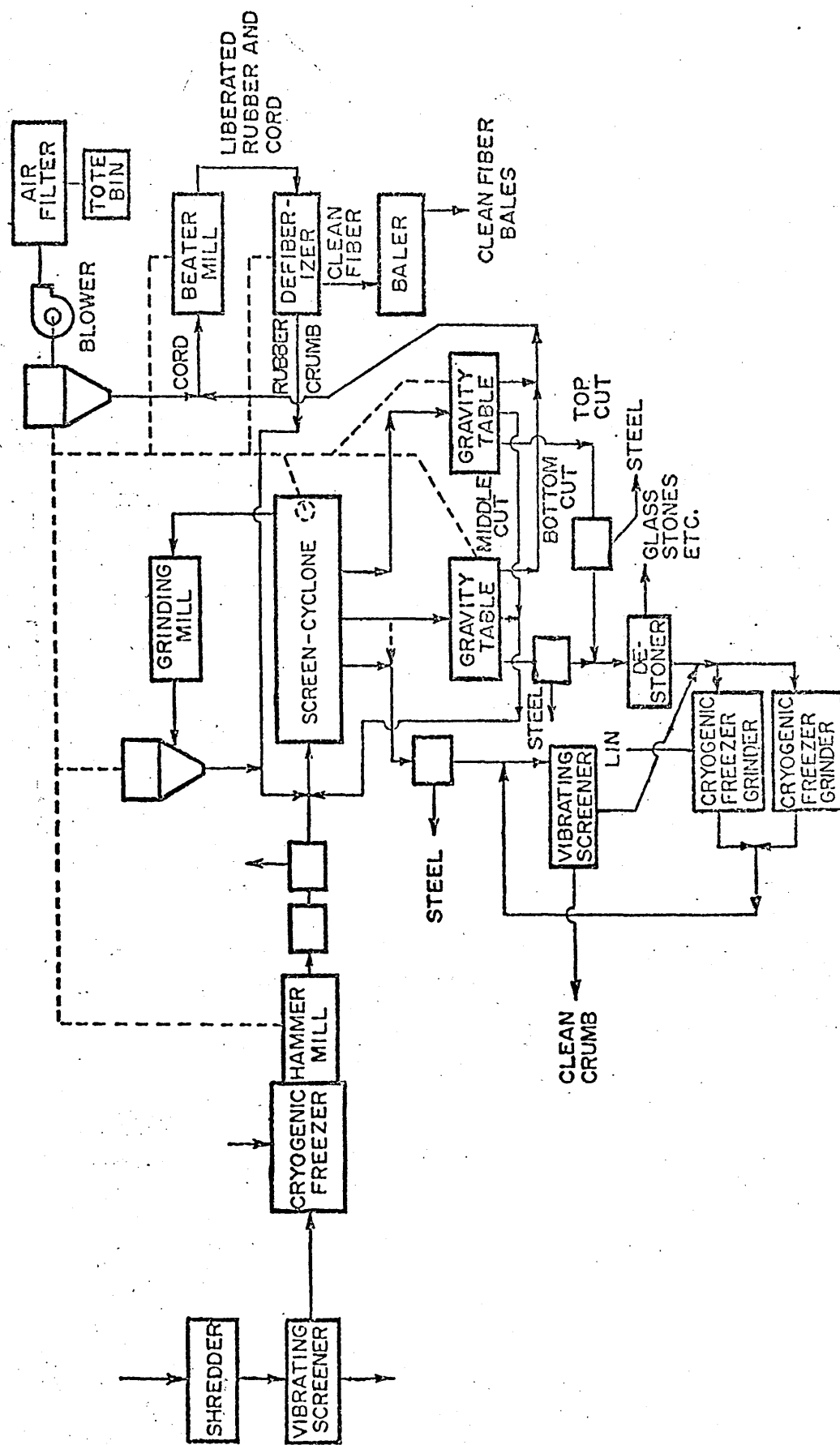


FIGURE B.4 Schematic Flow Diagram of the Air Products Process (from US Patent 4 025 990 (111))

The 20 mm rubber particles are passed under a series of magnetic separators, removing most of the steel/ferrous magnetic separators are divided into two fractions, namely the magnetic and the non-magnetic fractions. The magnetic fraction consists of about 99% of the steel present in a tyre, and from which steel is reclaimed. The non-magnetic fraction consists typically of about 90% of rubber crumb, 10% of fabric and less than 1% of steel, and this is conveyed to a screen cyclone.

In the screen cyclone, the classifying screen in the cyclone separator further separates the non-magnetic fraction into 4 streams. The top overs consist of oversize particles and are reground and returned to the screen cyclone. The second overs obtained from the second screen are further classified in a gravity table into top cut, middle cut and bottom cut. The top cut consists of mainly heavier rubber crumb. This is conveyed through a magnetic separator and a de-stoner to a cryogenic freezer-grinder which grinds it into fine particles. The fine particles are screened, the bottoms are clean crumb output from the process while the overs are returned to the freezer-grinder. The middle cut consists of fibre cord with attached rubber and some rubber crumb. This is conveyed back to the screen cyclone. The bottom cut, consisting of lighter fibre cords with small amount of attached rubber, is conveyed to a beater mill where rubber and fibre cord are separated. The liberated fibre cord and rubber-crumb pass through a de-fibriser where fibre cords are removed and baled, while the rubber crumb is returned to the screen cyclone for further classification.

The third overs from the screen cyclone, consisting of particles with sizes of less than 10 mesh (2 mm) but greater than 20 mesh (0.85 mm), are conveyed to a separate gravity table. In the vibrating gravity table, the particles are classified into 3 similar cuts as in the case for the second over fraction, and the corresponding cuts are treated accordingly.

The third bottoms consists of particles with sizes of less than 20 mesh (0.85 mm) and are conveyed through a magnetic separator to the final vibrating classifying screen. The overs are conveyed to the cryogenic freezer-grinder to effect further size reduction. The bottoms are the clean rubber crumb product.

The particle size of the rubber crumb depends on the size of the final screen, and preferable size of 30 mesh and smaller is quoted.

A smaller, simplified, version of the process is shown diagrammatically in Figure B.5. The version is aimed at rubber product manufacturers who are interested in in-house scrap recycling. Factory scrap rubber consists mainly of moulding flash, transfer pads, injection moulding sprues and runners, trimmings and rejected products, and usually does not contain any foreign materials. The scrap is first reduced to small pieces of about 10 mm size in an ambient granulator. The granulated product is fed to the loading hopper of the cryogenic freezer. The rubber granules are conveyed either by a Archimedian screw or a mesh-type conveyor belt, along the freezing tunnel where liquid nitrogen is sprayed directly on them. The liquid nitrogen instantly vapourises on contacting the rubber granules, absorbing from them the heat of vapourisation. The cold nitrogen gas follows a counter-flow direction, precooling the in-coming rubber granules before exiting from a venting valve. The embrittled rubber granules are fed to a grinding mill via a metering zone. Further freezing, if necessary, can be achieved by sprays of liquid nitrogen in the metering zone. The embrittled rubber is ground to fine crumb of desirable size.

(b) Cryogenic Grinding - The Bellaire Hydraulic Process

This whole scrap tyre cryogenic grinding process is invented by Mr Vernon C H Richardson (US Patent 3 718 284, 1977 (116)), and the processing units are marketed by Bellaire Hydraulics Inc, USA. Two units, a stationary and a portable, are reported to have been built for the Gulf Coast Waste Disposal Authority of Texas, USA. Each unit is reported to be able to handle 5000 tyres per 8-hour day, recovering 2.5 tonnes per hour of rubber crumb greater than 6.35 mm ($\frac{1}{4}$ inch), 850 kg per hour of fine crumb with size less than 6.35 mm, and 680 kg of scrap steel per day (62).

Figure B.6 shows the process diagrammatically. Whole tyres are conveyed horizontally from ground level, through a punch which makes holes on the sidewalls of the tyres allowing liquid nitrogen to chain effectively, into a primary treating zone. A flexible door arrangement prevents cold nitrogen gas from escaping from the zone. In the primary treating zone, the punched tyres are sprayed with liquid nitrogen to effect precooling

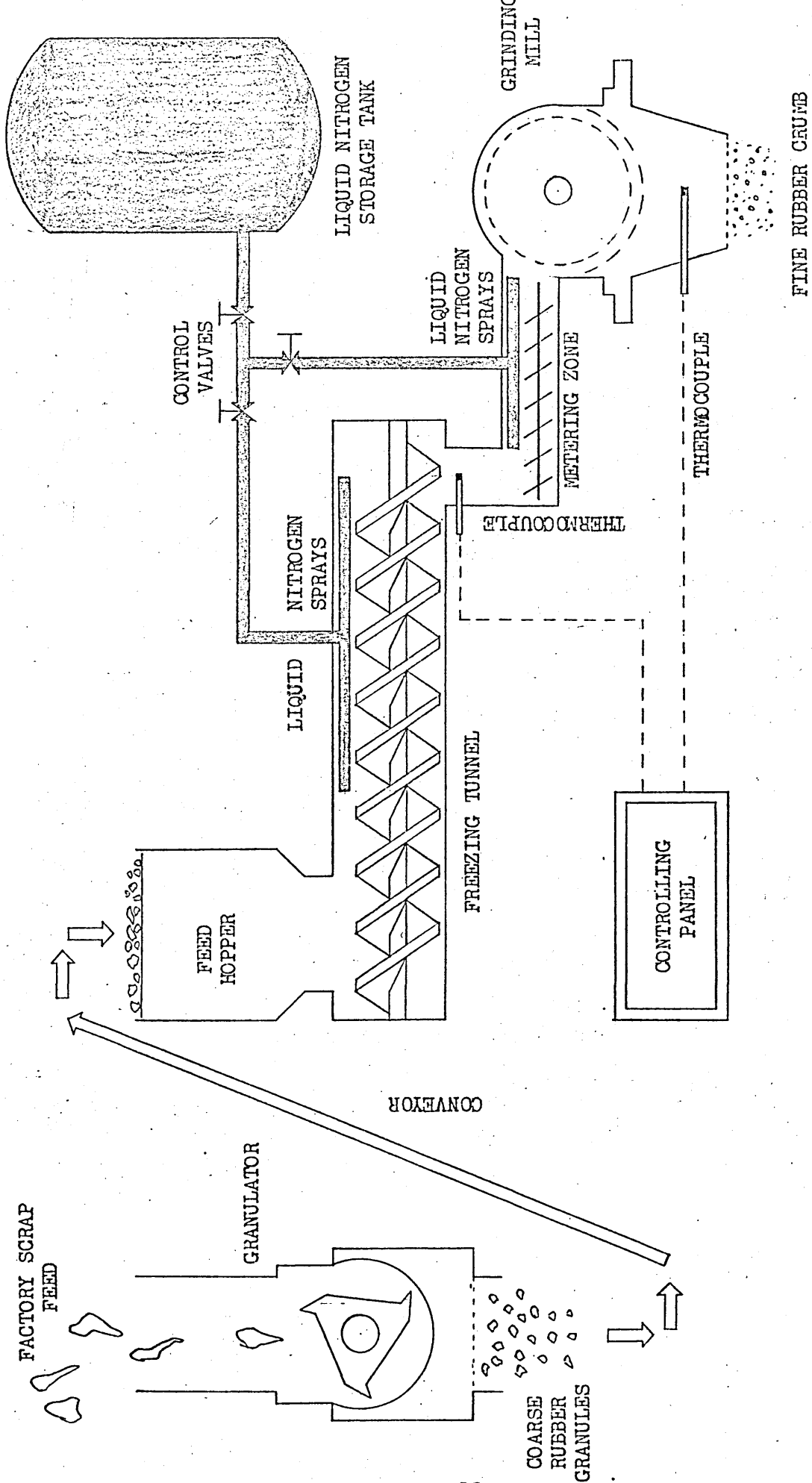


FIGURE B.5 Schematic Flow Diagram of the Air Products Process - Version II

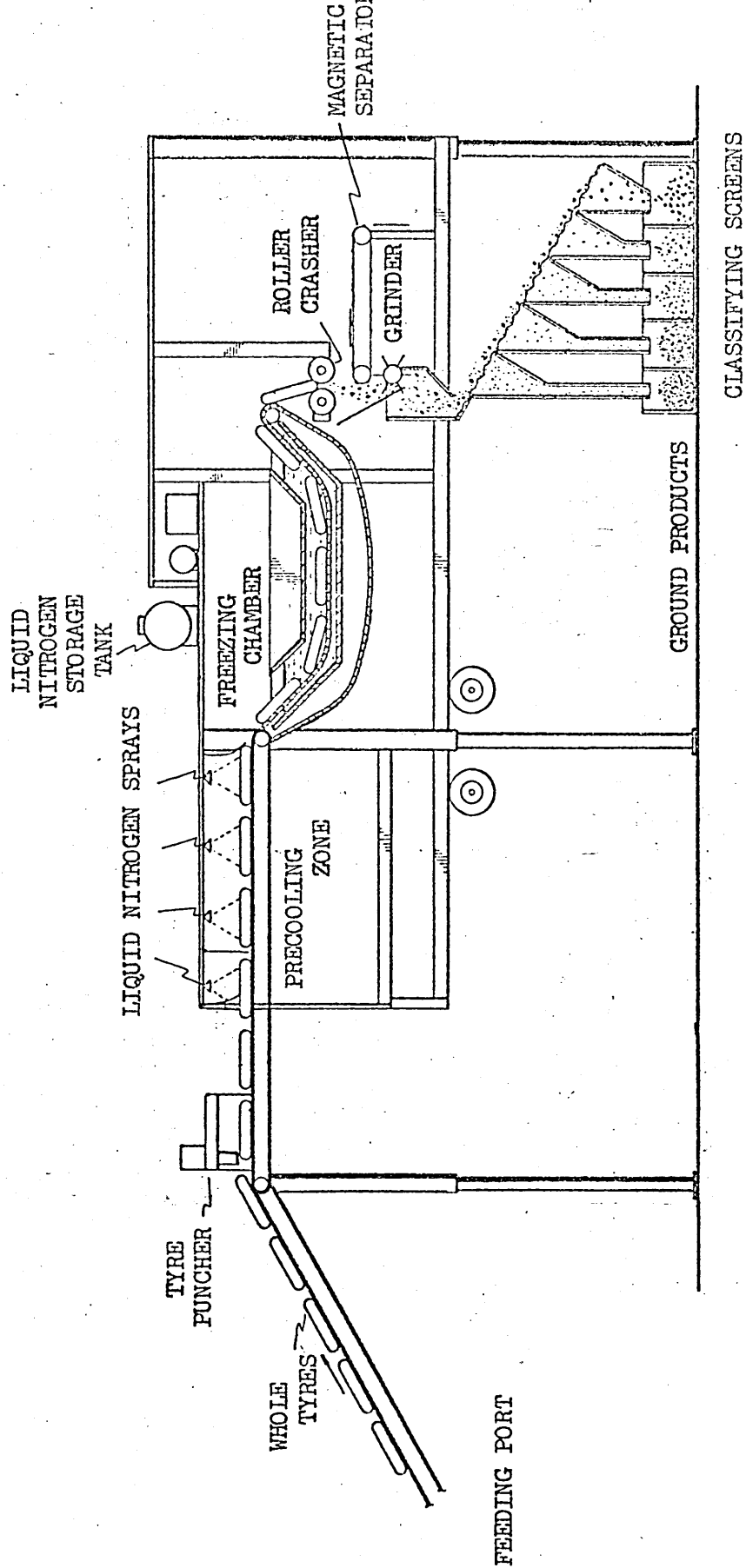


FIGURE B.6 Schematic Flow Diagram of the Bellaire Hydraulics Process (from Richardson (116))

before the tyres are conveyed into a liquid nitrogen bath. The tyres are kept submerged in the bath and are cooled to a temperature of about -65°C on leaving the bath.

The embrittled tyres are then passed between a pair of crushing rollers to crush the embrittled rubber and releasing the bead wires from the tyres. The bead wires are removed by a belt magnetic separator. The crushed tyres from the crushing rollers falls into the hopper of a hammer mill where subsequent grinding/pulverising is effected. The output from the hammer mill passes on to an inclined screen classifier where various sizes of tyre particles are obtained. Typically, 25% of the output is less than 6.35 mm.

This process differs from the Air Products process in several important aspects. Firstly, this Richardson process does not remove fabric components, hence the output rubber crumb will contain a high proportion, if not all, of the fibre present in the tyres. Secondly, the particles produced are much too large (6 mm), therefore cannot be used to advantage as a fine crumb (40 mesh or below). It is therefore an intermediate process. The intermediate nature of this process means that it is dependent on a secondary process to carry out fine crumb production. Lastly, whole tyres are cooled to embrittlement temperature in this process whilst in the Air Products process, shredding of the tyres is prior to freezing them. More efficient freezing can be achieved with the latter as the smaller shredded pieces have a large total surface area of contact with liquid nitrogen or cold nitrogen gas.

(c) Cryogenic Grinding - The Hazemag Process

This cryogenic tyre grinding process is developed by Hazemag Dr E Andreas KG of Germany, and is marketed in America by Hazemag USA Inc. The patented impact grinder, a rotary hammer mill, is described in US Patent 3 997 121 (1976) (107). The process has a design capacity of 660 car tyres per hour (approximately $6\text{ kg} \times 600 = 3600\text{ kg}$ per hour). The input has the limitation of accepting tyres with sizes between 13 to 16 inches with maximum belt width of 135 mm.

Figure B.7 shows the schematic diagram for the process. Whole tyres are manually hooked in rows on a conveyor in the feeding part. The tyres then pass through a freezing tunnel where liquid nitrogen is sprayed on

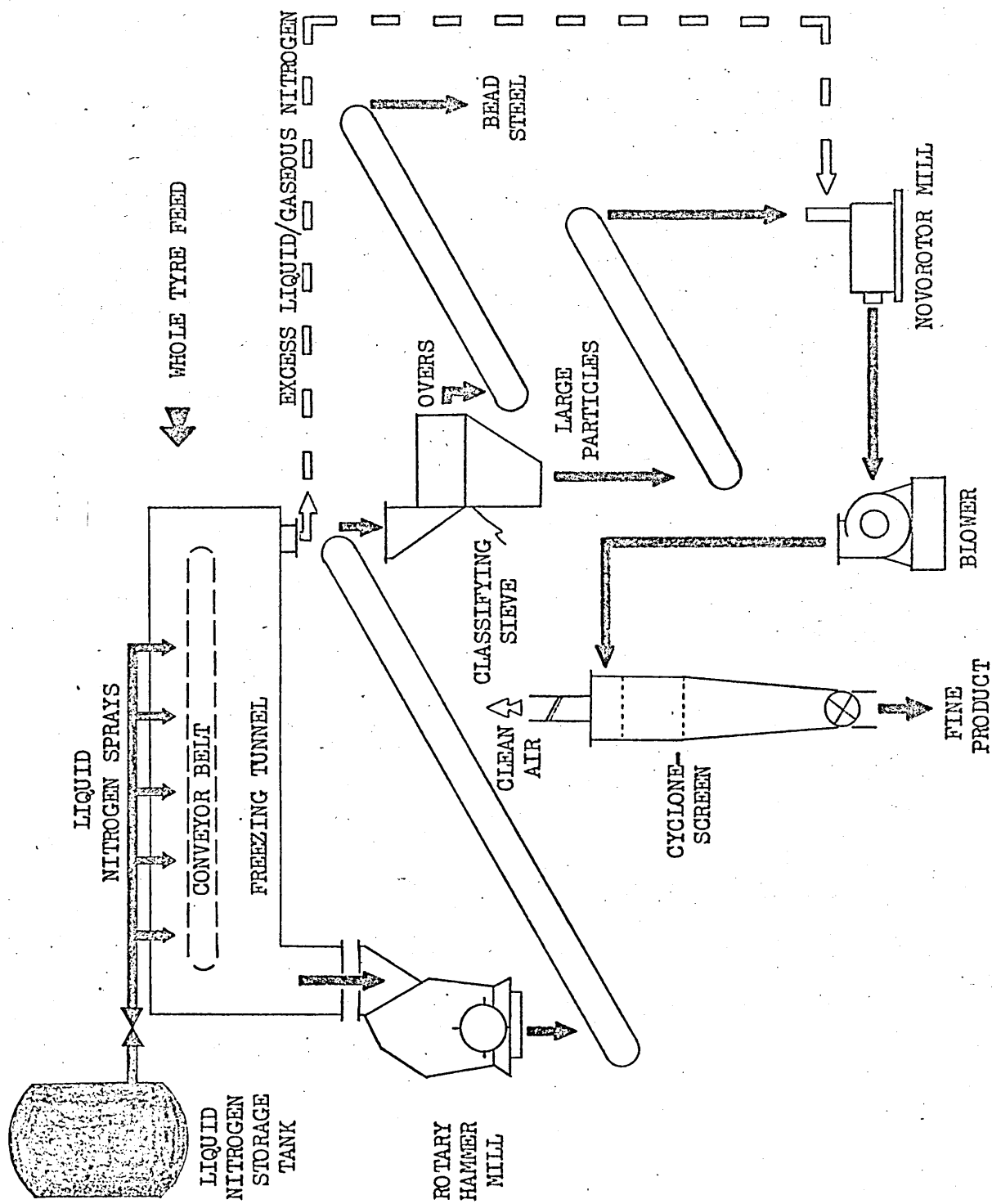


FIGURE B.7 Schematic Flow Diagram of the Hazemag Process (from Hazemag (107))

them to make them brittle. On reaching the other end of the freezing tunnel, the tyres automatically disengage and fall into the impact grinder. The embrittled tyres should ideally stay in a vertical position when reaching the rotor of the grinder. The striking elements of the rotor hit the embrittled tyre, crushing it and at the same time throwing the pieces towards some impact plates which effect further pulverisation. This combined action of the crushings separates completely, or almost completely, the rubber from the fabric and metal components.

The pulverised tyre is conveyed to a sieving/screening system where steel and fibre components are removed. The large rubber particles are conveyed to a Novorotor mill (manufactured by Hazemag) for further grinding. The output from the Novorotor mill is collected in a cyclone-screen where rubber crumb is classified. 90% of the output is less than 1 mm in size.

This process is very similar to the Air Products' except for the following aspects : firstly, this process does not require the shredding of whole before freezing; secondly, it has a unique patented rotary hammer mill which is claimed to be able to pulverise the rubber and liberate the fabric and steel reinforcements at the same time.

(d) Cryogenic Grinding - The BOC-KEK Process (121, 125)

This system has been developed by BOC International Ltd and KEK. KEK is responsible for the grinding and sifting operations while the freezing technology is supplied by BOC (126).

The grinding system is shown schematically in Figure B.8.

The starting material is metal and fabric-free scrap rubber granules of about 6 mm size, which is fed into the hopper of the screw freezer/conveyor. Sprays of liquid nitrogen are introduced into the screw freezer system where the rubber granules are conveyed along an inclined slope of the conveyor. Ideally, a pool of liquid nitrogen will form at the lower end of the screw conveyor effecting precooling of the rubber granules.

The embrittled rubber granules exiting from the screw freezer at a

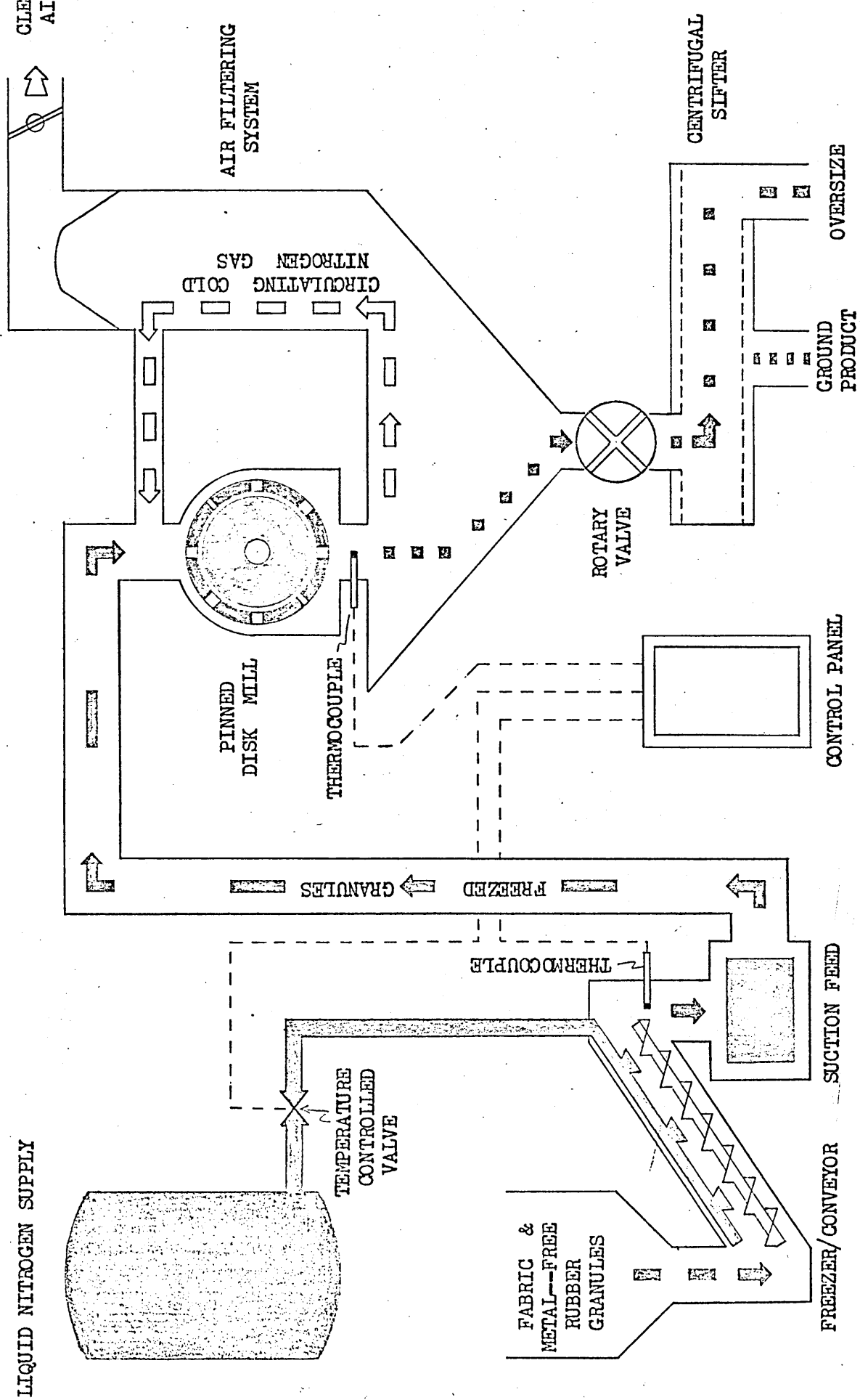


FIGURE B.8 Schematic Flow Diagram of the BOC-KEK Process

predetermined rate are dropped into a suction feed milling system. The suction feed mixes the frozen granules with a defined proportion of air, and then feeds granules to the pinned disk mill of KEK's design. The finely ground crumb is collected in a hopper, while the exhaust, cold nitrogen gas is recycled back into the suction feed system forming a closed circuit gas flow. Excess air is filtered to remove micronised particles before being emitted into the atmosphere.

A rotary valve is employed to remove a controlled amount of ground rubber crumb, which is then fed into the centrifugal sifter. A rotary brush in the sifter creates agitation and hence improves the speed and efficiency of sifting. Two product fractions are obtained, the crumb with desirable size, and the oversize particles. (The overs will not be fed back into the grinding system as this upsets the consistency of the feedstock, hence the rate of screw conveyor and the suction feed system.)

Temperature controls are by means of strategically positioned thermocouples and a temperature controlled valve. One thermocouple is located at the exit of the screw conveyor monitoring indirectly the temperature of the frozen rubber granules, while another thermocouple is placed at the exit of the mill determining the temperature of the output. The temperature information is fed to a control system which activates the temperature controller governing the injection of liquid nitrogen.

This process is not capable of handling whole tyres or shredded or cracked whole tyre.

(e) Cryogrind and Chemical - The Trellfax Process (28, 29, 30, 31)

This is a partial cryogenic grinding and partial chemical reclaiming process. It enjoys the unique ability of cryogenic operation to obtain fine rubber crumb free from metal and fabrics, and employs a reclaiming agent(s) to partially devulcanize the fine rubber particles.

Figure B.9 shows the flow chart for the process. Whole scrap tyres are shredded in a chopper, which are then chilled to the embrittlement temperature in a rotary freezing tunnel. The embrittled tyre pieces are subjected to three grinding stages, namely coarse, medium and fine

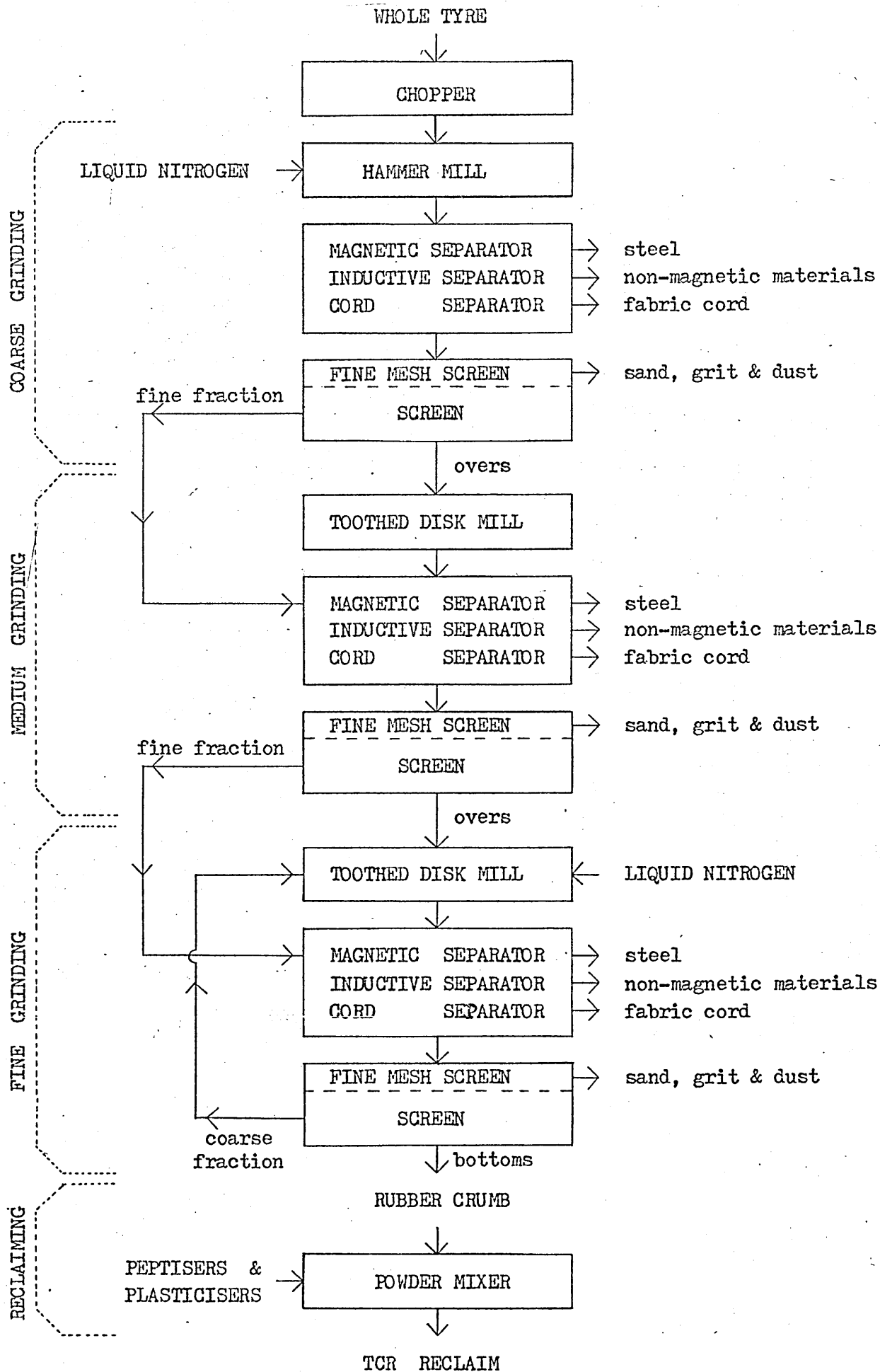


FIGURE B.9 Schematic Flow Diagram of the Trellfax Process

grinding. A hammer mill is used to pulverise the embrittled tyres pieces in the coarse grinding stage. The coarsely ground tyre crumb, with size of about 25 mm squares is then passed through a series of magnetic, inductive and cord separators removing ferrous scrap, non-magnetic materials and tyre cord textiles respectively from the tyre crumb. The coarse crumb then passes through a very fine mesh screen to remove sand and grit before reaching a screening system. In the screen sifter, the rubber crumb is sifted into various size fractions. The fine fraction bypasses the next grinding stage but always passes through the series of separators.

The medium grinder is a toothed disk mill. The output from the medium grinder is joined by the fine fraction from the coarse grinding stage, and passes through a series of separators, fine screen and sifter.

The final stage of the grinding process is carried out in a toothed disk mill fitted with fine grinding disks which differ from that of the medium grinder by having a denser and more grinding teeth on the disks. After sifting, the finely ground, metal-free, fabric-free tyre rubber crumb is stored in silos for the next reclaiming stage.

The chemical reclaiming is carried out in a powder mixer at room or slightly elevated temperature (about 50°C). Low temperature rubber reclaiming requires highly reactive chemical reagents. Details of the chemical reagents used are not available; however, phenylhydrazin and diphenyl guanidine systems are suggested to be suitable (28). Recent Japanese work (7, 8, 9, 120) reveals that a combination of phenylhydrazin and iron II chloride showed a synergistic effect for low temperature rubber reclaiming. Typically a phenylhydrazin - iron II chloride system for reclaiming passenger car tyre rubber crumb is as follows:

Ingredient	Part by Weight
Rubber Crumb	100
Phenylhydrazin	0.5 - 1
Iron II chloride	0.25 - 1
Cumarone (cumarone - indene resin)	5 - 8
Benzene	10 - 30
Methanol	6 - 10

The solvents, benzene and methanol are removed after reclaiming time elapses. The mixing time is about 10 minutes, during which time the reclaiming agents devulcanize at least the surface of the fine rubber particles giving them a rough surface finish. The roughness on the surface is claimed (28) to have improved the reinforcing properties of the rubber crumb. The output is termed Trelleborg Cold Regenerated Rubber (TCR) and it is a free flow powder. A plant based on this process has been in operation in Trelleborg AB, Surahammar, Sweden, since early 1981. This plant has a design capacity of 8000 tonnes of both TCR and rubber crumb output annually.

(f) Swell and Grind - The Gould Process (108, 109)

This process is based on US Patent 4 046 834 (1977) (108) and 4 049 588 (1977) (109). The Gould plant, situated in Cleveland, Ohio, USA, has a design production capacity of 1500 tonnes per year of output (26).

There is no published account of the actual production machinery, however, the principle underlying the process and the production procedure are clearly documented in the patents. Coarsely ground rubber crumb, about 30 mesh, is first swollen by a suitable reagent, thus weakening the whole vulcanized rubber matrix which is subsequently ground, removing the swelling agent at the same time or after that, thus obtaining finely comminuted rubber particles. Two manufacturing techniques are described in the patents.

Method 1 : (A 3 step process)

(1) Addition of up to 15% by weight of a fatty acid (such as oleic acid, stearic acid, tall oil fatty acids or resin acids) to coarsely ground vulcanized rubber crumb, allowing the fatty acid to absorb into the rubber crumb. The fatty acid acts as a swelling agent, swelling the vulcanized rubber matrix, hence weakening the rubber network. The resultant plasticised rubber crumb is sheeted with a tight-nip two roll mill.

(2) Addition of 2 to 25 phr of a solid alkali to the sheeted plasticised rubber crumb. Solid alkali such as Sodium Hydroxide or Potassium Hydroxide is dusted onto the sheet. Mechanical working is applied to the dusted sheet, by extruding the mixture, until a friable product is obtained. The solid alkali neutralises the fatty acid, forming a water soluble salt which subsequently removed in the next step.

(3) Dispersing the friable product in water to form an aqueous dispersion of a finely ground rubber particle. The salt of the fatty acid acts as a dispersing agent. The dispersion is achieved by grinding a mixture of the friable product and water in a toothed disk mill. Dry powdered rubber crumb is obtained by conventional means such as acid coagulation or physical separation, washed to remove the remaining traces of reagents and dried at low temperature.

A typical dosage of chemical reagents for processing whole tyre crumb are 3 parts of oleic acid and 10 parts of Sodium Hydroxide per hundred parts of rubber crumb.

Method 2 : (A 3 step process)

(1) Swelling of vulcanized scrap rubber. This is achieved by soaking shredded or crumb vulcanized scrap rubber in a suitable liquid swelling agent, allowing it to imbibe as much of the liquid as the rubber can take (for a defined period of time). The primary requirements for such a swelling agent are firstly, it must be able to swell the vulcanized rubber at a sufficiently fast rate; secondly, it must not react with the rubber; thirdly, it must be easily extractable. Tetrahydrofuran, Methyl-Ethyl-Ketone, Ethyl Acetate and Chloroform are suitable swelling agents.

(2) Comminution of the swollen rubber. This is carried in a suitable grinder for example, a toothed disk mill. Water is introduced, together with the swollen rubber into the grinder where the rubber is ground to a desirable degree of fineness. By choosing a suitable swelling agent, preferably a water miscible type for example Tetrahydrofuran, the swelling agent is thus extracted from the rubber as it is being comminuted. The resulting product is a mixture of water and swelling agent and the finely ground rubber crumb.

(3) Removal of liquid from the mixture. In the case of water miscible swelling agent, a simple filtering system may be employed. The fine crumb can then be dried in a suitable drying system. The swelling agent can be recovered from the filtrate by distillation.

Tetrahydrofuran is hinted to be the most suitable swelling agent for using in this method. Tetrahydrofuran (THF) satisfies the requirements for a swelling agent, it swells vulcanized rubber at a fast rate and does not react with the rubber. THF has a higher solubility parameter

with water than with rubber, therefore when finely ground swollen rubber crumb is mixed with water, the THF will leave the rubber and mixed with water, thus effecting swelling agent extraction.

The product obtained by this process is claimed to be 90% below 20 μ m effective diameter, and offers a viable economy. Gould Inc. of Cleveland, Ohio, USA, is presently offering a custom grinding service utilising this process (19, 26, 27).

B.3 Other Processes

(a) Microwave - The Goodyear Process (117, 118, 119)

This microwave devulcanization process is developed by Goodyear Tire & Rubber Company, and is described in UK Patent Application 2 028 835 A (1980) (84). Goodyear is reported to have used this process to recycle factory scrap from its Lincoln (Neb., USA) hose and belting plant (26, 27). The attractiveness of the microwave technique lies on its speed, although not all types of rubber can be devulcanized by this method.

A schematic diagram of the process, as constructed from the descriptions in the patent application, is shown in Figure B.10. The primary requirement of scrap rubber which can be processed by the microwave technique is that it must be a polar or containing a polar additive. Microwave causes the polar elements in the rubber compound to vibrate, thus generating frictional heat internally within the rubber to effect devulcanization. Scrap rubber, in the form of moulding flash, trimmings etc, is granulated into particles of size less than 9.5 mm (3/8 in.). A partition agent, which prevents the tacky devulcanized rubber particles from sticking together and used in the loading of between 0.5 to 3 parts by weight, is mixed with 100 parts of granulated scrap rubber. Suitable partition agents are silica, clay, talc and silicates. The type and size of the partition agents will affect the efficiency. Hi-Si 215 and 233 Silicates are given in the patent application.

The granulated scrap rubber - partition agent mix is charged into a transport tube. The transport tube must be made from a material transparent to microwave of which ceramic and glass are examples. The transport tube is inclined at an angle of about 15° and rotated. The speed of rotation dictates the amount of material passing through the tube. The rubber particles on passing through the tube are bombarded

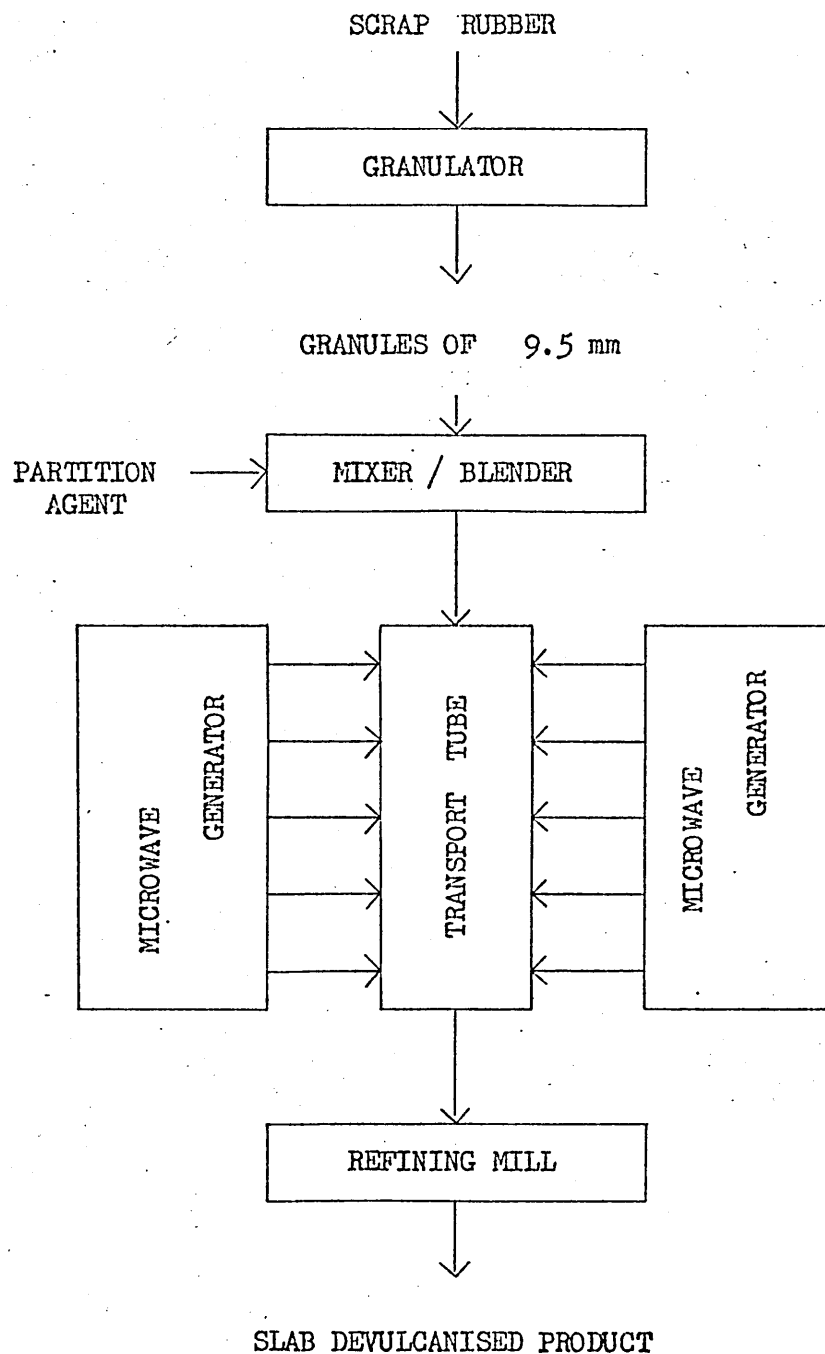


FIGURE B.10 Schematic Flow Diagram of the Goodyear Microwave Process

with a controlled dose of microwave energy. The dose rate and frequency of the microwave energy depend on the type of rubber and the compounding ingredients present in the scrap rubber particles. A dose of 50 to 150 watt-hours per pound, preferably 85 to 95 watt-hours per pound is recommended for general hose and belting rubber compounds. The frequency of the microwave has to fall within the range of 915 to 2450 MHz which is allocated for industrial applications, therefore would not interfere with radio frequencies.

The devulcanized scrap rubber exiting from the transport tube is refined in the conventional means and stacked into slabs.

The process is claimed to be able to reclaim more than 95% of input scrap rubber, and the output has none or minimal effect on physical properties and can be incorporated up to 25% (84).

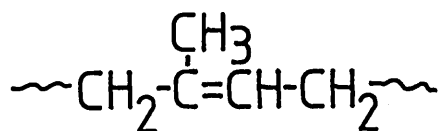
MECHANICS OF ELASTOMERS

Rubbery materials possess unique physical properties such as high degree of elasticity and extensibility. These unique properties result from the chemical composition and the molecular architecture of the material, and are exploited in a wide variety of end-use applications such as vehicle tyres, flexible hose and belting, and seals. From a technological point of view, the most important physical properties of a rubber are the elastic modulus, strength, tear resistance, abrasion resistance and resilience. The influence of physical and chemical parameters on the properties of rubber has been reviewed many times in the literature, see for example Whelan and Lee (135), Blow (72) and Morton (51). The following is a brief review of the important physical properties.

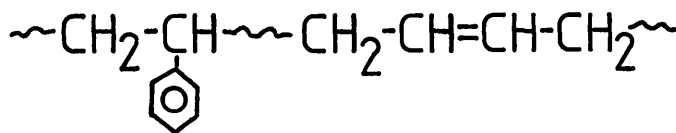
C.1 General Consideration

In the uncrosslinked (or unvulcanized) state, a rubbery material can be thought of as a disordered mass of highly convoluted macromolecular chains. Each molecular chain is made-up of basic repeat units, or 'chemical building blocks'. Typically a rubber macromolecule of molecular weight of approximately 35,000 has about 7000 repeat units in the chain. The chemical structures of the repeat units in some common rubbers are shown in Figure C.1

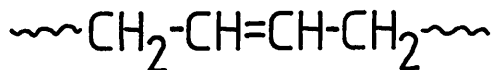
At room temperature the molecular chains of rubbers are in a state of continuous motion, both rotational and vibrational. It is the ease of chain segment rotation which imparts the properties of flexibility and high extensibility. Because of the absence of strong primary bonds between the macromolecules, the molecular chains are able to slip over each other under the action of applied stress. The unvulcanized rubber is said to exhibit the property of viscous flow, or creep. (This assumes that there are no severe chain entanglements, see Figure C.3). In order to promote dimensional stability and to enhance the elastic properties, strong chemical bonds between the molecular chains are introduced. These bonds are called crosslinks and the process by which they are formed is called vulcanization. The most common used vulcanization system utilises sulphur as the crosslinking agent. The types of sulphur crosslinks found in rubber vulcanizates are illustrated in Figure C.2, together with examples of polysulphidic crosslinks in



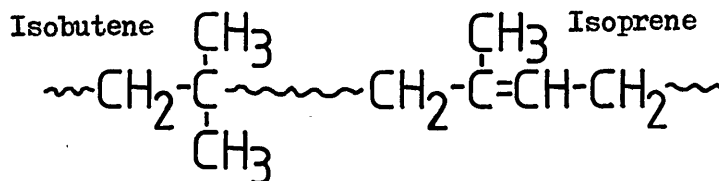
POLYISOPRENE & NATURAL RUBBER



STYRENE - BUTADIENE RUBBER

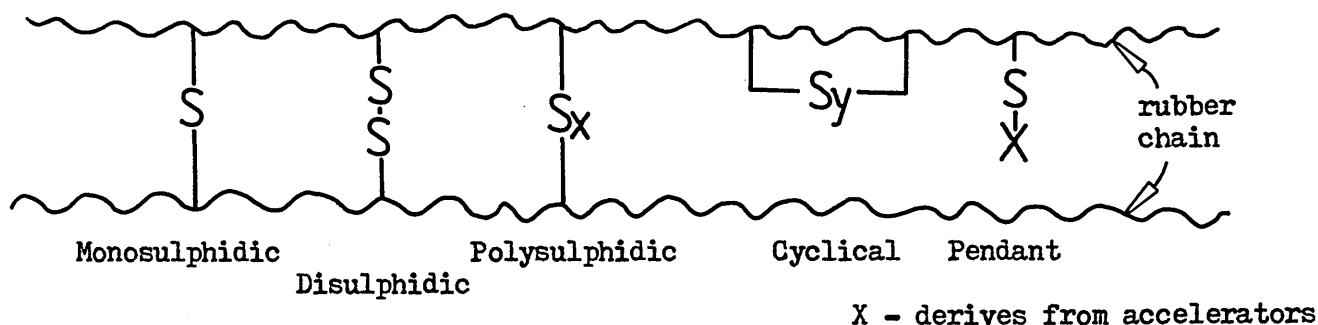


POLYBUTADIENE

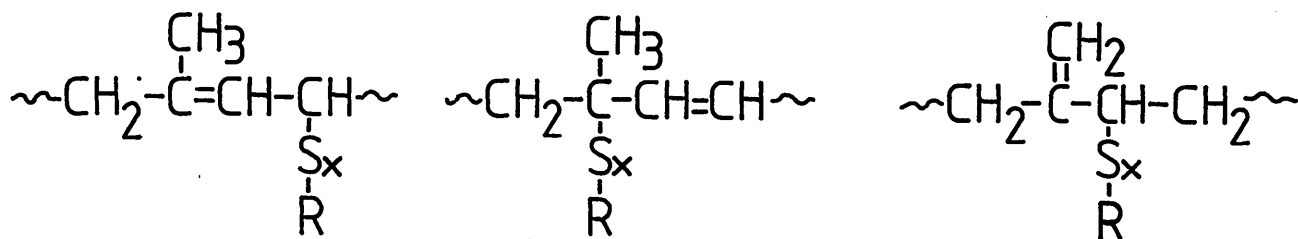


BUTYL RUBBER

FIGURE C.1 The Repeat Units of Some Common Rubbers.



TYPES OF SULPHUR CROSSLINKS



R = rubber molecule .

POSSIBLE POSITIONS OF POLYSULPHIDIC CROSSLINKS ON AN ISOPRENE REPEAT UNIT

FIGURE C.2 Molecular Architectures in (Crosslinked) Rubber Vulcanizates.

natural rubber vulcanizate. The efficiency of crosslink formation i.e. the number of effective crosslinks formed per unit mass of crosslinking agent, depends largely on the type of rubber and the cure system, and can be considerably enhanced by the inclusion of cure accelerators and activators in the compounding recipe.

The introduction of crosslinks results in the formation of a three dimensional network of polymer chains. One of the most important structural parameters is the size of the network molecule (between two crosslinks, see Figure C.3). This size is usually expressed in term of network molecular weight, M_c , which decreases with increasing degree of crosslinking.

C.2 Stress-Strain Behaviour and Elastic Modulus

The stiffness, or flexibility, of a rubber is usually described by its elastic modulus. The kinetic (or gaussian) theory of rubber elasticity predicts the relationship between stress and strain to be (49, 131):

$$\sigma = \frac{E}{3} \left(\lambda - \frac{1}{\lambda^2} \right) \quad (C-1)$$

where σ is the engineering stress; $E = 3\rho RT/M_c = 3v_e RT$ is the tensile elastic modulus (Young's Modulus) and λ is the extension ratio (defined as the ratio of the instantaneous length and the initial undeformed length of the tensile specimen). M_c is the number average molecular weight of the network molecules; v_e is the number of effective network molecular chains per unit volume of rubber; ρ , the density; R , the universal gas constant and T is the absolute temperature. From the expression for E , it can be seen that the tensile modulus (or stiffness) is inversely proportional to the network molecular weight. That is, the modulus increase with increasing degree of crosslinking.

Figure C.4 shows a comparison between the stress-strain behaviours predicted by equation C.1 with that found experimentally. The kinetic theory is found to be valid only at low extensions of strains ($\epsilon = \lambda - 1$) less than about 50%. (It should be noted that the typical breaking strain of rubbery material is in the range of 500% to 1000%). Consequently, the value of the elastic modulus at 300% elongation ($\lambda = 4$) predicted by the kinetic theory does not agree with that found

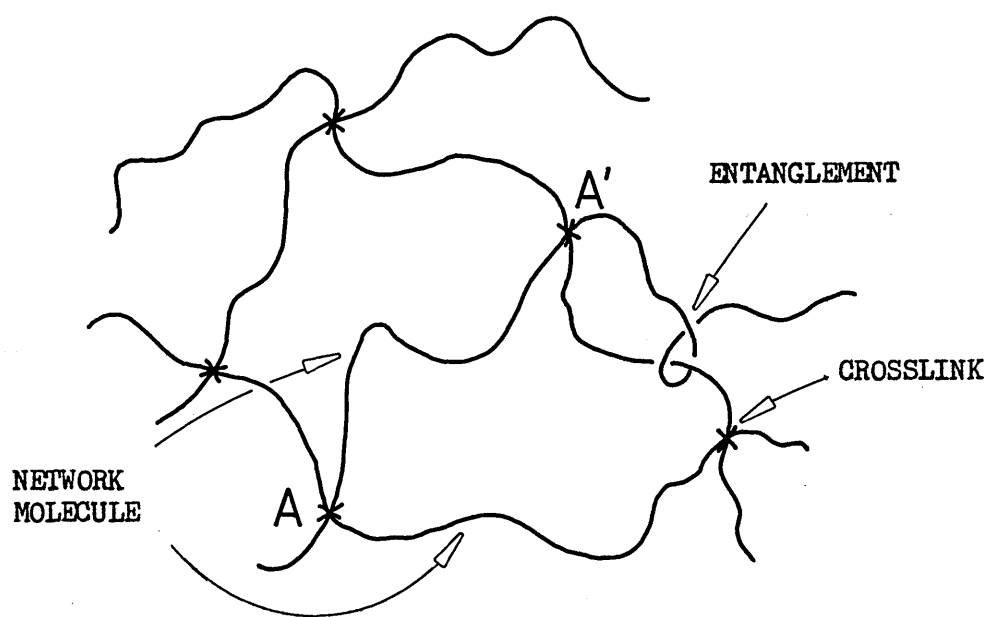


FIGURE C.3 Schematic Representation of a Crosslinked Rubber.
 AA' , the molecular chain between crosslinks. Important structure parameters: M_c , number average molecular weight of network molecule; v_e , number of effective network chains per unit volume of rubber.

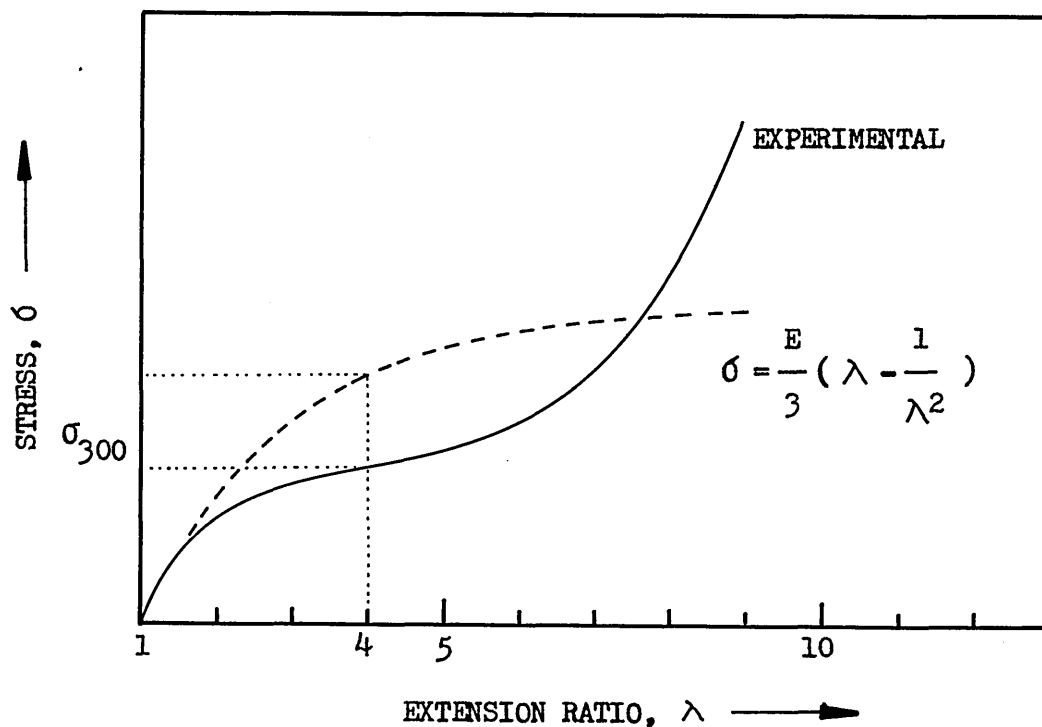


FIGURE C.4 Comparison of the Actual Stress - Strain Behaviour of an Elastomer with that Predicted by the Kinetic Theory of Rubber Elasticity, Equation C.1

in practice. In addition, the kinetic theory fails to predict the rapid up-turn in the stress-strain diagram at large strains. This failure is due primarily to the invalid assumption of a Gaussian (or random) orientation distribution of molecular chains when the rubber is extended (the network molecules become aligned in the direction of deformation on stretching).

At high extension ratios, the non-Gaussian theory may be used to predict the stress-strain relationship (131, 133). This can be expressed as:

$$\sigma = \frac{E}{9} \lambda_m \left\{ \mathcal{L}^{-1}(\lambda / \lambda_m) - \frac{1}{\lambda^{3/2}} \mathcal{L}^{-1}(1 / \lambda^{1/2} \lambda_m) \right\} \quad (C.2)$$

where λ_m is the extension ratio when $\sigma = \infty$ and approximates to the breaking extension ratio, λ_B . The value of λ_m is related to the number, n , of statistical segments (not the actual repeat units) in each network molecular chain by $\lambda_m = n^{1/2}$ is proportional to $1/v_e^{1/2}$. \mathcal{L}^{-1} is the inverse Langevin function which may be expanded into a series as:

$$\mathcal{L}^{-1}(x) = 3x + \frac{9}{5}x^3 + \frac{297}{175}x^5 + \frac{1539}{785}x^7 + \dots \quad (C.3)$$

Truncating the series after the first term gives the expression of the simple kinetic theory (equation C.1).

Equation C.2 is complex and difficult to apply to material property data. However, a simplified form has been used by Kaelble et al (147) in their analysis of the stress-strain behaviour of two phase elastomers. The approximate equation is:

$$\sigma = E_m \frac{(1 - 1/\lambda)}{1 - (\lambda/\lambda_m)^2} \quad (C.4)$$

where E_m is the terminal modulus, i.e. modulus at the breaking elongation.

Kaelble et al have also proposed a mathematical model which gives a complete description of the tensile stress-strain behaviour of two phase material systems. This is based on two analytic functions, one applies at small strains and the other at large strains. It is assumed there is a smooth transition between these two functions. The complete expression which is presented in terms of the real stress and strain, is:

$$\frac{\sigma}{\epsilon} = (E_0 - E_m)B_d + \frac{E_m}{1 - (\lambda/\lambda_m)^2} \quad (C.5)$$

where E_0 and E_m are the initial and terminal moduli and B_d is a debonding parameter. B_d has a value between unity and zero depending on the strain. The value of B_d is taken as an indication of the degree of bonding between the two phases. Kaelble et al (147) and Hodgkinson (132) have used this expression to analyse debonding in triblock copolymer elastomers. As discussed in Appendix D, debonding between filler and matrix is an important feature of the mechanics of rubber-rubber composites at large strains. This debonding process could be studied using an expression similar to that given by equation C.5.

Although the elastic modulus is an important characteristic of a rubber, the stiffness of the material is usually described in terms of its hardness. The hardness is probably the most widely measured property of a rubber, and is done by measuring the depth of penetration of a spherical or conical indenter under a dead load. The indentation is then converted to hardness (usually in IRHD, International Rubber Hardness Degree). Since hardness measurements are carried out at small strains, there is a direct relationship between hardness degree and initial tensile modulus (148). This relationship is shown in Figure C.5.

The hardness of a rubber compound can be changed in three ways: (i) by varying the number of crosslinks formed during vulcanization, this controls the network molecular weight; (ii) by introducing an extender or plasticiser, which reduces hardness; (iii) by the introduction of a filler. When rigid particulate fillers are used, which is usually the case, the hardness is increased.

C.3 Tensile Strength

The tensile strength is another commonly specified physical property, although in most practical applications it does not play a direct role. The strength of a rubber compound (a term used to describe a rubber composition which usually includes a base rubber, a curing system, filler, softener/plasticiser and protective agents) is influenced by a number of variables, the most important being the type of rubber used, the crosslink density and the type and amount of filler. In general, the strength of a rubber compound increases with increasing crosslink

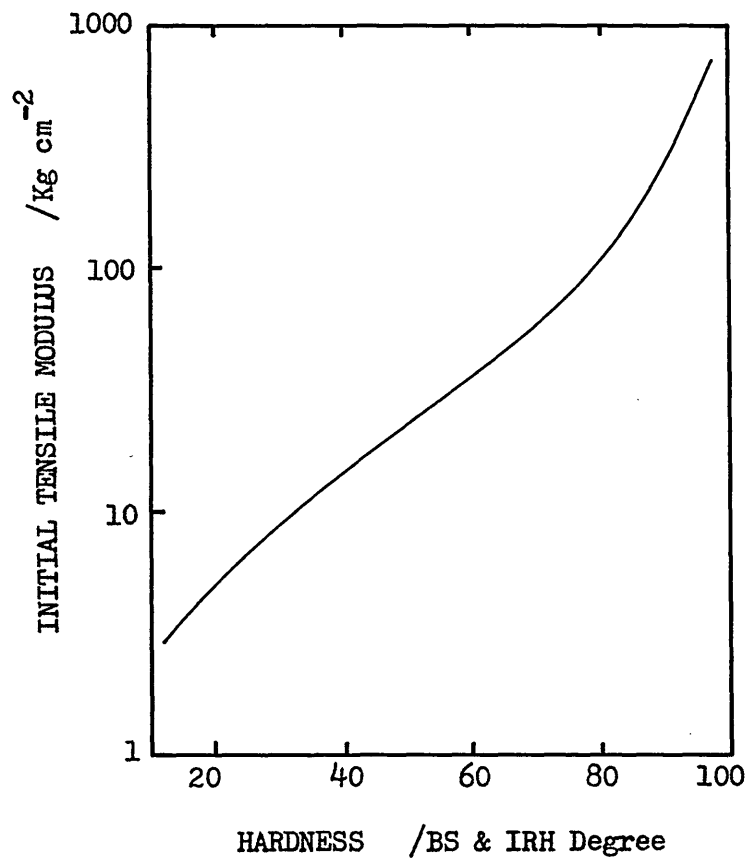


FIGURE C.5 Relationship Between Elastic Modulus and Hardness
(from Gent (148))

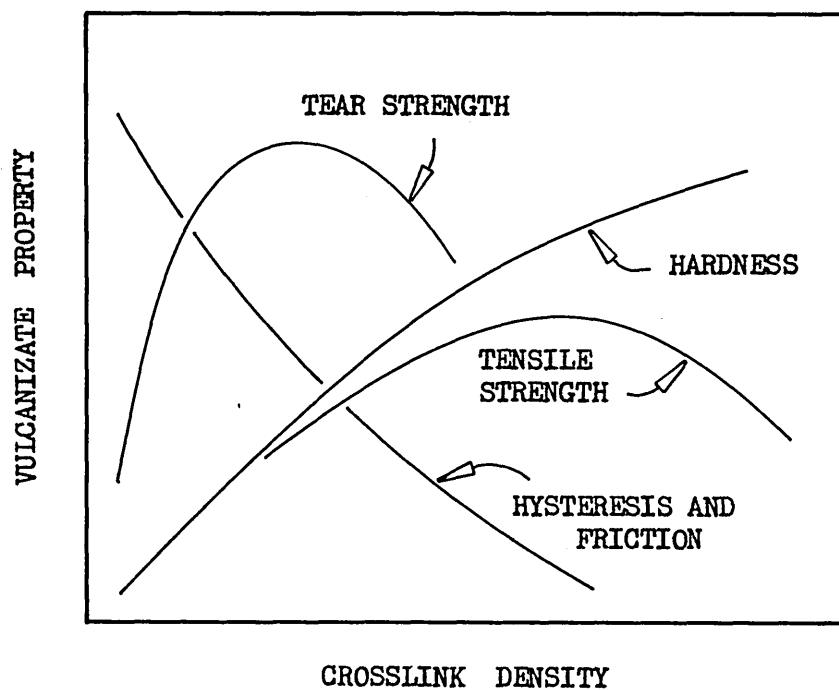


FIGURE C.6 Influence of Crosslink Density on the Mechanical Properties
of a Rubber Compound

density, but passes through a maximum value. The influence of crosslink density on some mechanical properties of a rubber compound is shown schematically in Figure C.6.

When compounding rubbers, it is usual (sometimes essential) to incorporate fillers into the system. These fillers can be classified into two categories: (i) reinforcing fillers, e.g. carbon black and high surface silicas, which have high unit cost, and (ii) non-reinforcing (also known as bulking, diluent or inert) fillers, e.g. clay and calcium carbonate, which have low unit cost (135). Reinforced rubbers are considered to be those whose tensile strength and abrasion resistance are markedly improved from their corresponding unfilled rubbers. The primary requirements for reinforcement are the filler particles bond (i.e. adhere) to the rubber matrix, they must have effective diameters, d_{eff} , in the submicron range, and they must not agglomerate excessively in the rubber matrix (72, 135). Fillers with particle size range of a few to several hundreds of micrometres, produce little or no reinforcement. The incorporation of a non-reinforcing filler usually results in a lowering of the physical properties.

Several workers have derived equations relating the tensile strength to molecular and structural parameters. For example, Bueche (133,149) has put forward the expression:

$$\sigma_B = (v_{\text{eff}}/3)^{2/3} F_c \quad (\text{C.6})$$

where v_{eff} is the number of crosslinks corrected for free chain ends and F_c is the tensile strength of a single chain. Unfortunately, this equation does not predict the maximum in the $\sigma_B - v_{\text{eff}}$ relationship which is found in practice (see Figure C.6).

Gent (133) has argued that rubber fracture is essentially a tearing process, the tear being initiated at some inhomogeneity, or flaw in the material. For a perfectly linear elastic material, he showed that the stress at break is given by:

$$\sigma_B = (TE/\pi C)^{1/2} \quad (\text{C.7})$$

where T is the tear energy, E the elastic modulus and C the diameter of the flaw. This expression has been investigated experimentally by

artificially introducing flaws of known size. Using values of σ_B , T and E obtained from independent measurements, the inherent flaw size, C_0 , of the rubber compound can be calculated from equation C.7. Evidence indicates that this is typically about 20 μm (133,150). Although the assumption of linear elastic behaviour is not valid for elastomers, equation C.7 has been widely used to interpret the data for the strength properties of these materials.

C.4 Tear Strength

The tear strength is the force required to rupture a standard test piece having a specified cut introduced into it. Several different types of specimen configurations are used, such as the trouser and the crescent test pieces (51, 72). Each configuration will give a different tear strength, which may not correlate with tear strength obtained by other configuration. The tear strength is directly related to the tear energy, T , of the material. This parameter has been widely investigated and it has been shown that approximately (133, 150):

$$T = d W_B \quad (C.8)$$

where d is the effective diameter of the tip of the tear, and W_B is the intrinsic breaking energy of the rubber. W_B is defined as the energy required to break unit volume of the material in the absence of a significant nick or flaw. Both W_B and d depend on the conditions of tear. It has also been shown that W_B is related to the internal viscosity of the material, which is often described in terms of the loss modulus. This parameter is discussed briefly later. The breaking energy is dependent on the temperature, rate of tear and the rate at which the material is deformed to rupture at the tear tip.

Experimentally, the value of the tear strength is influenced by the crosslink density and fillers (72, 133). However, the mechanisms involved are not clearly understood. In general, any mechanism which enhances the hysteresis of the material (loss modulus or internal viscosity) also leads to enhanced tear strength. Some of these mechanisms may also cause a reduction in the tensile strength. Thus it is not uncommon to find that, when manipulating a particular rubber compounding variable, the tear strength increases whereas the tensile strength decreases. Fine particulate fillers, such as reinforcing silicas and aluminium silicas, tend to give better improvements in

tear strength than reinforcing carbon blacks (72).

The enhancement of the tear strength by fillers can be related to two independent factors: (i) the effective diameter of the tear tip, d , and (ii) the intrinsic breaking strength, W_B , which is governed to a large extent by the hysteresis of the material. The mechanisms that have been put forward to explain tear strength enhancement have been reviewed by Gent (133). They include particle matrix interactions (such as load sharing, chain slippage, particle debonding and multiple internal failure resulting from the tear propagating from particle to particle), molecular processes (such as stress softening, which leads to increased hysteresis) and tear tip deviation on a macroscopic scale (resulting from frozen-in stresses or blunting of the crack tip).

C.5 Resilience and Hysteresis

Rubber products are often employed in situations where they are subjected to oscillatory deformation, e.g. vehicle tyres. When the rubber is taken through a deformation cycle, only part of the energy used in deforming the material is returned to the mechanism responsible for the deformation. The energy which is not returned during the unloading part of the cycle, appears in many different forms such as noise. However, the most important energy transformation is the conversion of strain energy into heat energy. Since the thermal conductivity of rubber is small, the heat energy cannot dissipate rapidly to the local environment. This leads to an increase in the temperature of the material which may cause the degradation of polymer chains and the failure of the product.

Heat build-up in rubbery materials is usually described by means of a material property called hysteresis H , or its inverse or more commonly measured property, resilience R .

The resilience is defined as:

$$R = \frac{\text{Energy recovered during a Deformation Cycle}}{\text{Energy input to the Deformation Cycle}} \quad (\text{C.9})$$

and the hysteresis is:

$$H = 1 - R \quad (\text{C.10})$$

These parameters are usually expressed as percentages. A more precise parameter, which is widely used to describe the conversion of strain energy into different forms, is the loss modulus. When a polymeric

material is taken through a strain cycle, in general the stress is out of phase with the strain, i.e. there is a time lag. This means that the stress can be factorised into two components, the stress in phase with the strain, σ' , and the stress 90° out of phase with the strain, σ'' . It is therefore possible to define two dynamic moduli, which are:

$$\text{Storage Modulus, } E' = \frac{\sigma'}{\epsilon_0}$$

and

$$\text{Loss Modulus, } E'' = \frac{\sigma''}{\epsilon_0}$$

where ϵ_0 is the amplitude of the oscillatory strain. The loss is directly related to the internal viscosity of the material. In practice the dissipative nature of the material is not always described by its loss modulus, E'' , but by the loss tangent, $\tan \delta$, which is defined as:

$$\tan \delta = \frac{E''}{E'}$$

$\tan \delta$, in effect, is a measure of the ratio of the energy dissipated to the energy stored during a deformation cycle.

The hysteresis, H , of a rubber is increased by the incorporation of fillers, but decreases with increasing degree of crosslinking (see Figure C.6). Under end-use conditions, the value of H also depends on T_g and the plasticiser content.

C.6 Abrasion Resistance

Abrasion resistance of a rubber compound is a measure of the resistance to abrasion (or frictional) wear. Abrasion is the removal of small particles of rubber from the surface by rupture, or tearing, under the action of frictional forces when sliding takes place between the rubber surface and a substrate. Thus, abrasion resistance is directly related to the tear energy, T , and hence the breaking energy, W_B , of the material (133, 136).

In practice, the abrasion resistance of a rubber compound depends on the temperature, rate of deformation, type of rubber and filler. This parameter has a maximum value at about the glass transition temperature but decreases at higher temperatures. It decreases with increasing rate of deformation, passes through a minimum and then increases at higher

rates (133). The dependence of abrasion resistance on the type and amount of filler is more complex. Fillers with higher surface activity which form strong bonds with the rubber matrix, show a better abrasion resistance because of their ability to dissipate large amounts of energy through these bonds (72, 136).

MECHANICS OF COMPOSITES

In considering the mechanics of recycled rubber-rubber composites, it is necessary to differentiate between the two distinct types of recycled rubber, namely (i) reclaimed rubber and (ii) vulcanized particulate rubber crumb or powder. In the first case, the recycled rubber is incorporated as an intimate mixture with the base rubber and this material system may be considered as a rubber-rubber blend. In the second case, the vulcanized rubber particles are bound into the vulcanized rubber matrix. Since the current economic and technological constraints indicate that the second of these recycling routes, i.e. recycling through rubber crumb production is probably the most feasible, it is necessary to consider the possible effects on mechanical properties of the rubber vulcanizates incorporated with this vulcanized rubber particle. In this type of material system, the particulate rubber may be considered as a filler. The ideal arrangement of such a system is shown schematically in Figure D.1. The important features are the properties of the matrix (or binding) material, the properties of the filler and the properties of the interfacial layer between the filler and the matrix.

Due to the complex geometry of filler particles, most of the mathematical models used for predicting the mechanical properties of particulate filled composites are either largely empirical in nature, or only provide approximations to the behaviour. The most widely used method is based on the simple law of mixtures for continuous fibre reinforced systems (151, 152). The parallel and series arrangements of such systems are shown in Figure D.2. It is necessary to make certain assumptions in establishing property relationships. One of the most critical of these is that there must be perfect adhesion (or bonding) between the reinforcement and the matrix. Since in many reinforced systems, it has been found that debonding occurs at large strains (see for example Reference 133, p467), the mathematical models have been most successful only in predicting material properties for low strain situations, e.g. the initial elastic modulus E_0 . With particulate filled systems, it is assumed that the initial elastic modulus $(E_0)_c$ (c denotes composite) lies within the upper and lower bounds, E_p and E_s respectively, predicted by the parallel and series arrangements of the continuous

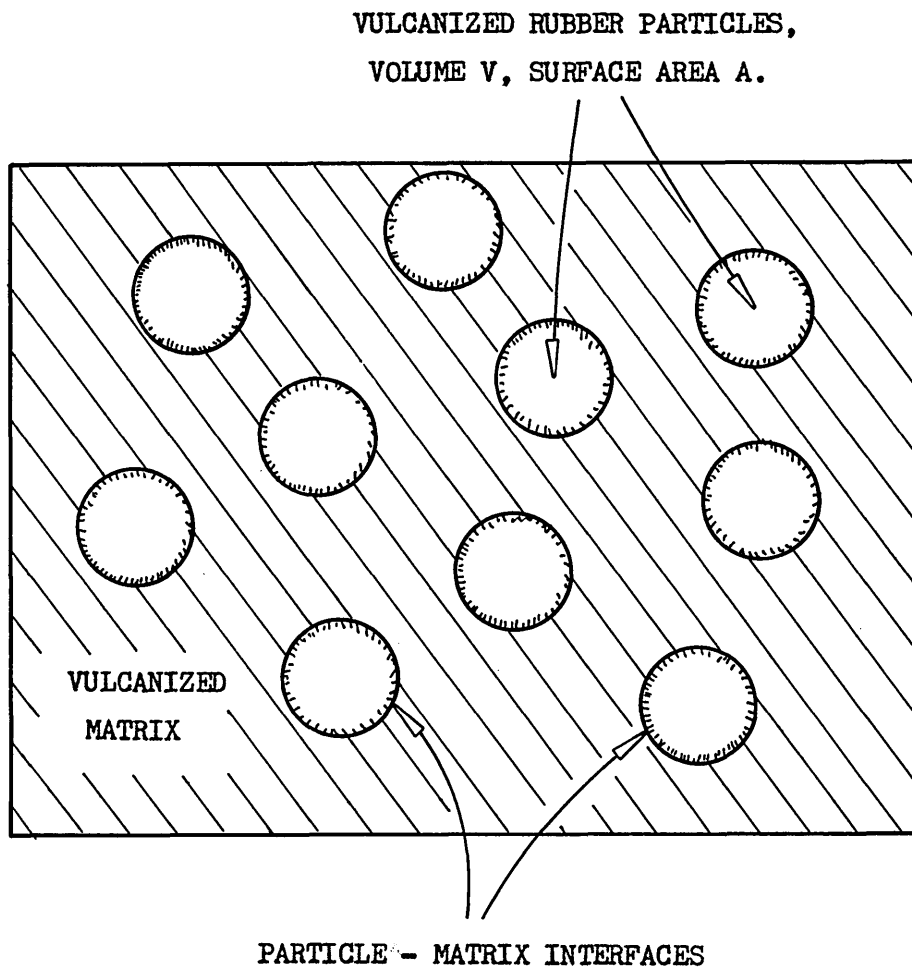


FIGURE D.1 Schematic Representation of A Particulate
Filled Rubber - Rubber Composite

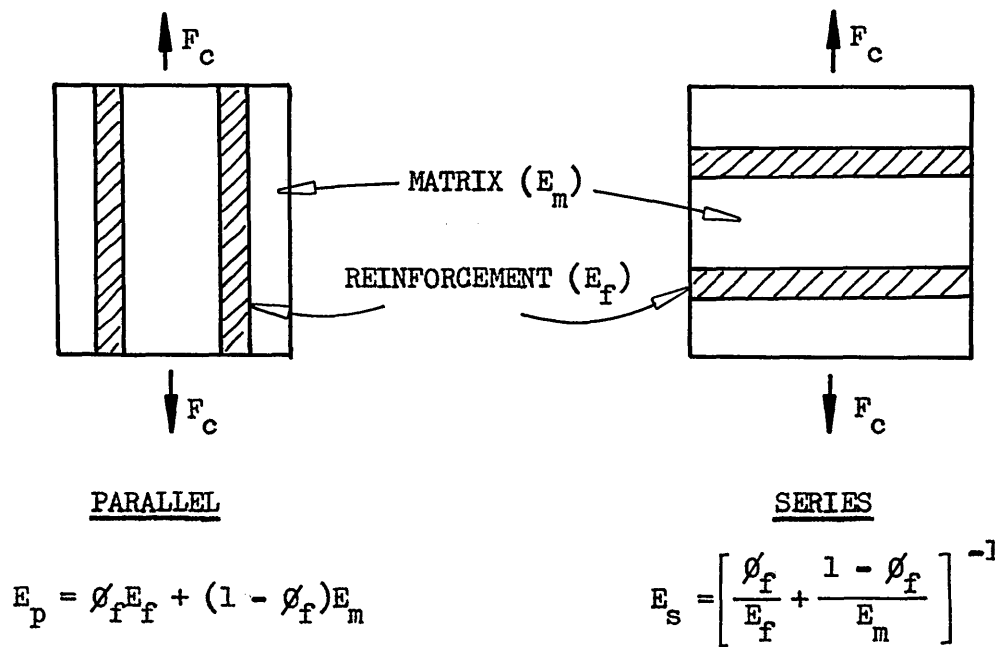


FIGURE D.2 The parallel and series models for continuous fibre reinforced materials. E_f and E_m are the elastic moduli of the fibre reinforcement and the polymer matrix respectively, and ϕ_f is the volume fraction of the reinforcing material, $\phi_f = V_f/V$ where V_f is the volume of reinforcement and V is the total volume.

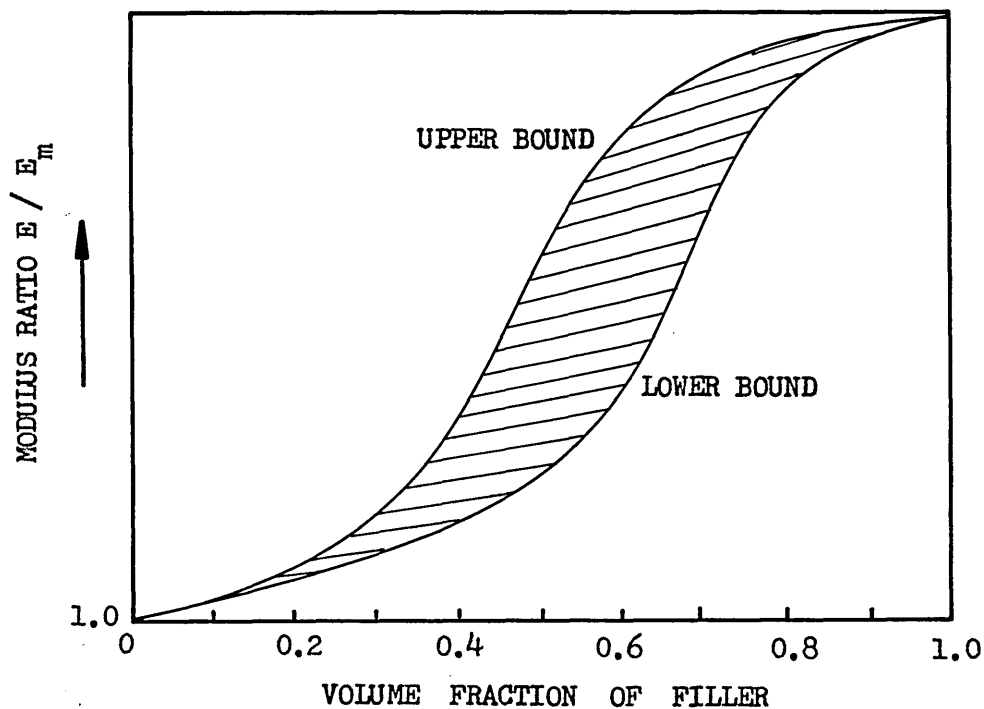


FIGURE D.3 The upper and lower bounds for the elastic modulus of composites (see for example Nielsen (156))

fillers (refer Figure D.3). E_p and E_s can be expressed in terms of parameters relating to rubber-rubber composites as:

$$E_p = \phi_{RR} E_{RR} + (1 - \phi_{RR}) E_m$$

$$E_s = \left[\frac{\phi_{RR}}{E_{RR}} + \frac{(1 - \phi_{RR})}{E_m} \right]^{-1} \quad (D.1)$$

where ϕ_{RR} is the volume fraction of recycled rubber, and E_{RR} and E_m are the elastic moduli of the rubber particles and the rubber matrix respectively. Ashby and Jones (152) have stated that the properties of particulate filled polymers are closer to the lower bound, E_s , given by equation D.1. A better approximation can be obtained by using some averaging technique. Several of these have been described in the literature. One particular relationship which has been used previously to analyse the elastic properties of rubber-thermoplastic composites is (153, 154):

$$(E_o)_c = p(E_p - E_s) + E_s \quad (D.2)$$

where the parameter p depends on the volume fraction of filler ϕ_{RR} and a curve fitting constant n . p can take values between 0 and 1. This constant n is influenced by the shape of the dispersed particles, the wetting of the particles by the matrix material, the thermodynamic compatibility etc. and varies from system to system. n takes into account many of the unknown factors.

A well-established mathematical model for the modulus of two phase materials is that due to Kerner (155), which has been discussed, for polymeric composites, by Nielsen (156). Assuming that for rubber-rubber composites, the Poisson's ratio, γ , for the two phases is equal to 0.5, and that the modulus of the particulate rubber filler is related to the modulus of the rubber matrix by $E_{RR} = \alpha E_m$, then the Kerner equation for the ratio of the modulus of the composite, $(E_o)_c$ to the modulus of the matrix, $(E_o)_m$ reduces to:

$$\frac{(E_o)_c}{(E_o)_m} = \frac{\frac{\phi_{RR} \alpha}{4.5 + 3\alpha} + \frac{1 - \phi_{RR}}{7.5}}{\frac{\phi_{RR}}{4.5 + 3\alpha} + \frac{1 - \phi_{RR}}{7.5}} \quad (D.3)$$

The modulus ratio in situations where the modulus of the RR is larger ($\alpha > 1$) and smaller ($\alpha < 1$) than that of the rubber matrix is shown in Figure D.4. Assuming that there is perfect bonding between filler and matrix, it can be seen that the modulus is predicted, by equation D.3, to increase with ϕ_{RR} for $\alpha > 1$ and decrease if $\alpha < 1$. That is the greater the modulus of the particular rubber filler (hence its hardness), the greater will be modulus of the composite, and smaller E_{RR} reduces the modulus of the composite. Equation D.3 also predicts that when

$\alpha = 1$, or $E_{RR} = E_m$, the modulus of the composite is equal to E_m . Dickie (157) found that for particulate rubber filler - thermoplastic system, Kerner's equation tends to underestimate the filler concentration, ϕ_{RR} and suggested that a correction factor should be added to ϕ_{RR} . It should be noted that the relationship is not rectilinear.

The strength (or ultimate) properties of particulate-containing composite materials are more dependent upon the geometry and size of the filler particles, and the interfacial contact between the two phases, than the initial elastic properties. For example, the stress concentration factor associated with inhomogeneities for particles having acute angular geometry is larger than that for spherical particles. There seems to be no theoretical model which can be used to predict the strength of particulate filled composites.

There are three major problems in developing such a theoretical model:

- (i) the bonding between rubber filler and rubber matrix;
- (ii) the distribution of stress around the filler; and
- (iii) the non-linear force deformation behaviour of elastomers.

If there is perfect bonding between filler and matrix, and the two phases have the same stress-strain properties, then the ultimate properties of the composite would be expected to be the same as those of the base rubber. This will not be the case if any important parameter, such as the modulus or elongation at break, is not balanced.

When a non-reinforcing, but well-wetted, rigid filler is incorporated into the material system, failure usually begins with cavitation in the rubber matrix at some distance from the filler-matrix interface (p.541, 133). A crack then propagates to the filler surface and de-wetting (or debonding) occurs. Failure may take place during, or after, de-wetting is complete, depending on the strength of the rubber matrix,

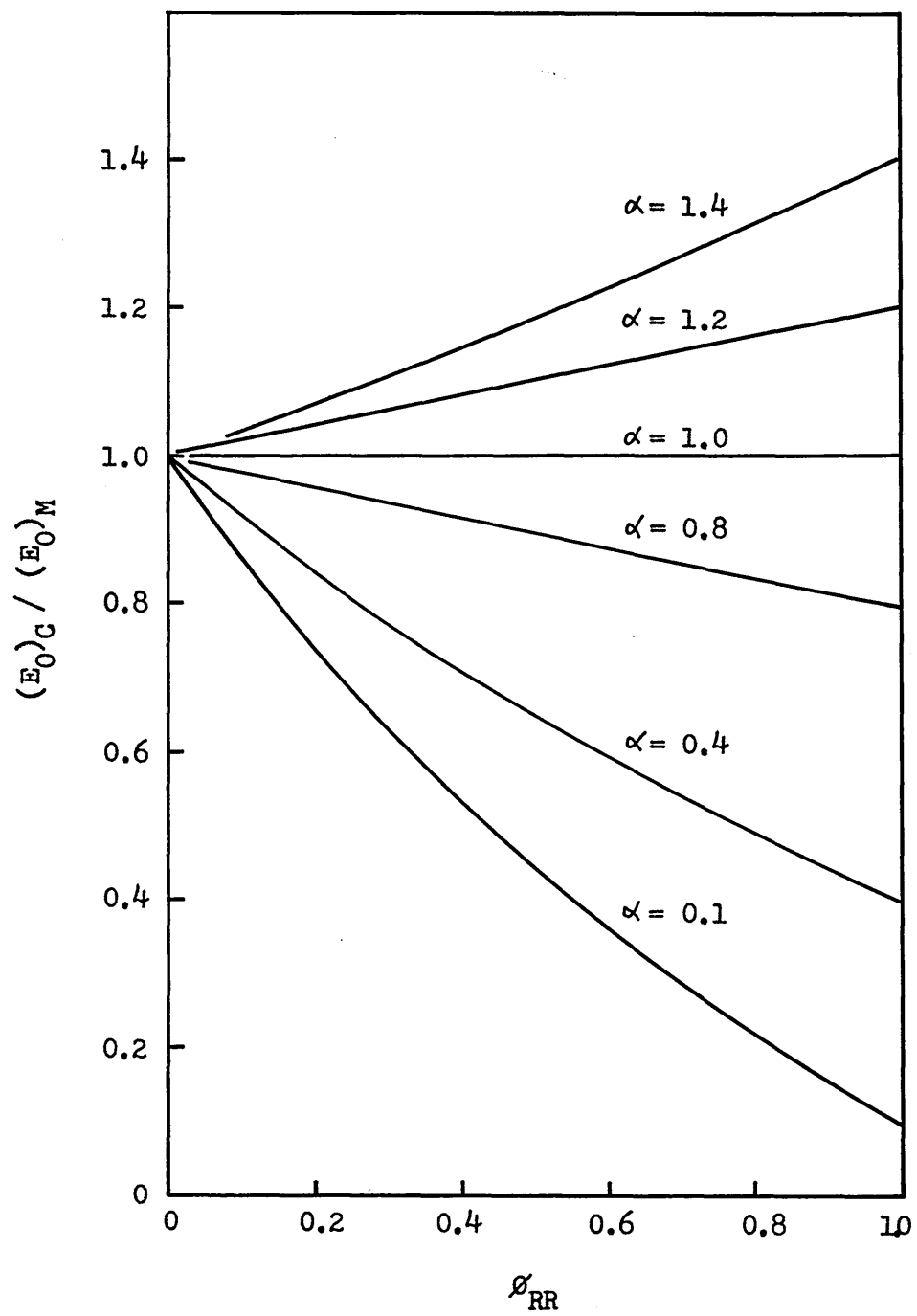


FIGURE D.4 Variation of the Modulus Ratio Predicted by Kerner Equation for Different Values of $\alpha = E_{RR} / E_M$

the volume fraction of filler and other factors. If the contact between filler and matrix is poor, failure may be initiated at interfacial areas where there is incomplete wetting between filler and matrix before deformation.

An example of debonding in a particulate rubber composite is shown in Figure D.5 which is a scanning electron micrograph of a cut surface of a particulate recycled rubber-thermoplastic composite. The craters resulting from the 'pulling out' of the rubber filler particles is clearly seen.

Some indication of the bounds for the strength of particulate composites can be obtained from the simple law of mixtures considered earlier.

Two situations may be considered:

- (i) perfect bonding between the filler and the matrix;
- (ii) the imperfect arrangement.

These two extreme situations for particulate fillers are shown schematically in Figure D.6. Accordingly to the description of Kelly (133, p459), a debonded particulate-filled system, approximates to a debonded fibre reinforced system. Mascia (151) has stated that for continuous fibre reinforced systems, the fracture stress $(\sigma_B)_c$ is given by:

$$(\sigma_B)_c = (1 - \phi_f) \hat{\sigma}_m \quad (D.4)$$

where $\hat{\sigma}_m$ is the value of the stress for the matrix at a strain equal to the breaking strain of the fibres. This fracture stress may be considered as indicating an approximate lower bound to the breaking strength of a particulate composite.

For a perfectly bonded continuous filament reinforced system, Mascia gives:

$$(\sigma_B)_c = \phi_f \hat{\sigma}_f + (1 - \phi_f) \hat{\sigma}_m \quad (D.5)$$

where $\hat{\sigma}_f$ is the breaking stress for the reinforcing fibres. This stress, as given by equation D.5, may be considered as an approximate upper bound to the ultimate strength of a particulate composite.

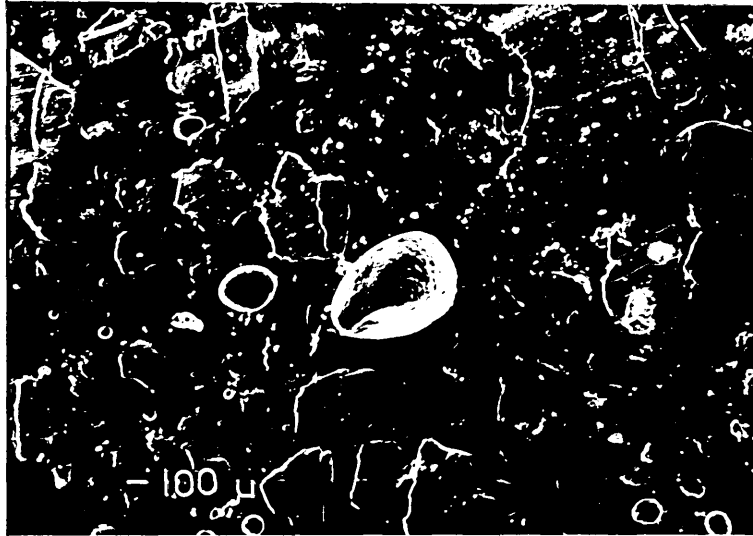


FIGURE D.5 Electron micrographs of the cut surface of a particulate rubber - thermoplastic composite.

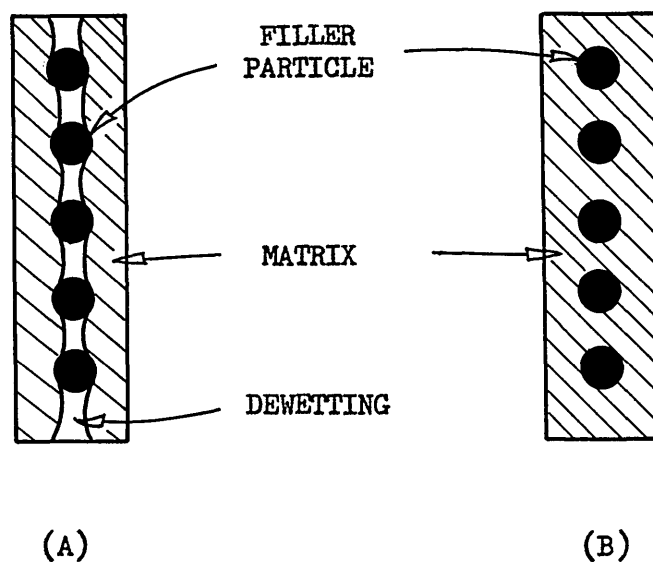


FIGURE D.6 Schematic Representation of the Morphology of A Two Phase Polymer Material System at large Strains. (A) Imperfect bonding between filler particles and matrix. (B) Perfect bonding. (from Eirich and Smith (133), based on Kelley)

In studying short fibre filled thermoplastic composites, McNally et al (161) had used a general form of this expression (equation D.5), for bonded system :

$$(E_0)_c = (1 - V_f)(E_0)_m + R (E_0)_f V_f \quad (D.6)$$

$$(\sigma_B)_c = (1 - V_f)(\sigma_B)_m + R'(\sigma_B)_f V_f \quad (D.7)$$

where V_f denotes the volume fraction of the filler. R and R' are termed reinforcement factors which are associated with adhesive bond strength between the matrix and filler at the interfacial layer. R and R' take the values of less than or equal to unity. Comparing equations D.5 and D.7, it can be seen that for perfect bonded system, $R' = 1$.

EXPERIMENTAL PROCEDURE AND RESULTS OF SBR-RR AND NR-RR COMPOSITE SYSTEMS

This Appendix describes the details of experimental procedure and variables, and the results of experiments carried out with vulcanizates incorporating whole tyre crumb, WTC, as recycled rubber. NR (Crusoe Standard powdered natural rubber supplied by Harrisons & Crosfield Ltd.) and SBR 1500 have been used as base rubber. The WTC used was 40 mesh (BS) ambient ground crumb supplied Dunlop Ltd.

The experimental work described in the Appendix is only a preliminary investigation which will lead to further more detailed systematic study. The desine to balance time and resources spend between the two aspects of rubber recycling i.e. economics and technology, meant that a thorough investigation of this multi-facet technological problem cannot be wanrated. The present investigation has concentrated more on the WTC-SBR 1500 composites than WTC-NR systems.

The results are presented in tables and in the form of graphs. No attempt will be made in the Appendix to interpret the results. These are evaluated in the appropriate sections in Chapter Five, together with the limited data available from published literature.

E.1 Compound Preparation

A conventional accelerated sulphur curing system based on MBTS (Dibenzthiazyl Disulphide) and ZDEC (Zinc Diethyl Dithiocarbamate) accelerators has been used. The sulphur levels have been increased arbitrarily, but the accelerators levels were increased in proportion to the total RHC contents. The detailed compound formulations for the rubber compounds, together with the vulcanization conditions are presented in Table E.1 and E.2.

The SBR and NR compounds were mixed in a laboratory two-roll mill at about 50°C. Large batches of the SBR and NR mixes, without WTC and curatives, were compounded first. These were subsequently weighed into appropriate portions. Appropriate amounts of crumb and curatives, according to the formulations, were then mixed into these portions individually. The resulting mixes are sheeted in the mill and were allowed to stand at room temperature for at least 24 hours. Moulding blanks of 50g each were obtained from these sheeted mixes. These are

then moulded in a hydraulic press at the appropriate vulcanization conditions as shown in Table E.1 and E.2. The curing time was varied according to the amount of curing agent incorporated into the mix, so as to optimise the cure of the matrix. The moulded sheets with a thickness of about 2 mm were allowed to stand in room temperature for at least 24 hours before physical testing was carried out.

The physical properties were determined using standard dumb-bell samples at a strain rate of 1.1 s^{-1} (cross-head speed of 5 cm s^{-1} and initial sample length of 4.5 cm). The stresses and strains obtained were engineering stresses and strains.

E.2 Results

The physical properties of the WTC-SBR1500 and WTC-NR composite systems are presented in Tables E.3 and E.4 respectively. The graphs for the systems are presented in the appropriate sections of chapter Five.

In order to facilitate the analysis of stress-strain behaviour of these material systems, the stress-strain diagrams, $\sigma - \lambda$, are represented in Figures E.1 through E.9. Two mathematical models are used in Section 5.4 (d) to describe the Gaussian and non-Gaussian behaviours of these materials. The Mooney-Rivlin equation, which applies at low extensions, can be written in the form:

$$\frac{\sigma}{2 \left(\lambda - \frac{1}{\lambda^2} \right)} = C_1 + \frac{C_2}{\lambda}$$

where C_1 and C_2 are constants characteristic of the rubber network. Hence, a plot of $\sigma/2 \left(\lambda - \lambda^{-2} \right)$ as a function of $1/\lambda$, usually termed Mooney-Rivlin plot, should yield a straight line. A simplified form of the non-Gaussian model based on the inverse Langevin expression, which applied at high extension, is used. This form of the non-Gaussian model, which has been proposed by Kaelble(147) and used by Hodgkinson(132), can be written in the form:

$$\frac{1 - \frac{1}{\lambda}}{\sigma} = \frac{1}{E_L} - \frac{\lambda^2}{E_L \lambda_L^2}$$

where E_L and λ_L are the terminal elastic modulus (at break) and the terminal extension ratio respectively. Again, a straight line is expected from a plot of $(1 - 1/\lambda)/\sigma$ against λ^2 . The data for these plots are contained in Tables E.5 and E.6.

Mooney-Rivlin plots and non-Gaussian plots for the two material systems are presented in Figures E.10 through E.19. The Mooney constants, C_1 and C_2 , for the material system obtained from the Mooney-Rivlin plots are given in Table E.7.

Table E.1 Compound Formulation for WTC - NR Mixes

Base Compound

<u>Ingredient</u>	<u>Phr</u>
NR (Crusoe Standard, Powdered)	100
Zinc Oxide	5
Stearic Acid	2
Antioxidant ⁺	1

⁺ 2,2' methylene bis (4-methyl-6-tertiary butyl phenol), Antioxidant 2246, Anchor Chemical (UK) Ltd.

Recycled Rubber and Curatives

a) Control mix

<u>Ingredient</u>	<u>Phr</u>
WT Crumb (40 mesh, ambient ground)	0
Sulphur	2.5
MBTS	1.0
ZDEC	0.1

b) Constant sulphur level mixes

<u>Ingredient</u>	<u>Phr</u>	
WT Crumb	20	50
Sulphur	2.5	2.5
MBTS	1.0	1.0
ZDEC	0.1	0.1
Total RHC ⁺⁺	110	125

⁺⁺ assuming WT Crumb contained 50% RHC

Sulphur content and vulcanizing conditions

<u>Sulphur (Phr)</u>	<u>Vulcanizing Time (Min)⁺</u>
1.0	30
1.5	25
2.0	20
5.0	15
10.0	15

⁺ at 150°C and pressure of one ton per sq. inch.

b) $\phi_{RR} = 20$ phr Series (with S = 1 to 10 phr)

<u>Ingredient</u>	<u>Phr</u>
WT Crumb	20
MBTS	1.65
ZDEC	0.22

Sulphur content and vulcanizing conditions

<u>Sulphur (Phr)</u>	<u>Vulcanizing Time (Min)⁺</u>
1.0	30
1.5	25
2.0	20
5.0	15
10.0	20

c) $\phi_{RR} = 50$ phr Series (with S = 1 to 10 phr)

<u>Ingredient</u>	<u>Phr</u>
WT Crumb	50
MBTS	1.875
ZDEC	0.25

Sulphur content and vulcanizing conditions

<u>Sulphur (Phr)</u>	<u>Vulcanizing Time (Min)⁺</u>
1.0	30
1.5	25
2.0	20
5.0	15
10.0	20

⁺ at 150°C and pressure of one ton per sq. inch

Sulphur content and vulcanizing conditions:

<u>Sulphur (phr)</u>	<u>Vulcanizing Time (min)⁺</u>
1.0	30
1.5	25
2.0	20
5.0	15
10.0	15

b) $\phi_{RR} = 20$ phr Series (with S = 1 to 10 phr)

<u>Ingredient</u>	<u>Phr</u>
WT Crumb	20
MBTS	1.65
ZDEC	0.22

Sulphur content and vulcanizing conditions:

<u>Sulphur</u>	<u>Vulcanizing Time (min)⁺</u>
1.0	30
1.5	25
2.0	20
5.0	15
10.0	20

c) $\phi_{RR} = 50$ phr Series (with S = 1 to 10 phr)

<u>Ingredient</u>	<u>Phr</u>
WT Crumb	50
MBTS	1.875
ZDEC	0.25

Sulphur content and vulcanizing conditions:

<u>Sulphur</u>	<u>Vulcanizing Time (min)⁺</u>
1.0	30
1.5	25
2.0	20
5.0	15
10.0	20

⁺ at 150°C and pressure of one ton per sq. inch.

c) Sulphur level adjusted for total RHC

<u>Ingredient</u>	<u>Phr</u>	
WT Crumb	20	50
Sulphur	2.75	3.125
MBTS	1.1	1.25
ZDEC	0.11	0.125
Total RHC	110	125

d) Sulphur saturated

<u>Ingredient</u>	<u>Phr</u>	
WT Crumb	20	50
Sulphur	10	10
MBTS	1.1	1.25
ZDEC	0.11	0.125
Total RHC	110	125

Vulcanizing Conditions

All mixes were cured at a temperature of 140°C for 15 minutes, at a pressure of one ton per square inch.

Table E.2 Compound Formulation for WTC - SBR Mixes

Base Compound

<u>Ingredient</u>	<u>Phr</u>
SBR 1500	100
Zinc Oxide	5
Stearic Acid	2
Antioxidant 2246	1

Recycled Rubber and Curatives

a) $\phi_{RR} = 0$ phr Series (with S = 1 to 10 phr)

<u>Ingredient</u>	<u>Phr</u>
WT Crumb	0
MBTS	1.5
ZDEC	0.2

Table E.3 Physical Properties of WTC-SBR 1500 Vulcanizates $\phi_{RR} = 0$ phr

<u>Sulphur Content(phr)</u>	<u>E_0 (MPa)</u>	<u>σ_B (MPa)</u>	<u>ϵ_B (%)</u>
1.0	0.99	1.00	777
1.5	0.98	0.91	665
2.0	1.02	0.89	654
5.0	1.42	1.21	293
10.0	2.38	1.91	194

 $\phi_{RR} = 20$ phr

<u>Sulphur Content(phr)</u>	<u>E_0 (MPa)</u>	<u>σ_B (MPa)</u>	<u>ϵ_B (%)</u>
1.0	1.34	1.66	677
1.5	1.47	1.51	530
2.0	1.51	1.53	460
5.0	2.54	1.91	187
10.0	3.14	2.24	126

 $\phi_{RR} = 50$ phr

<u>Sulphur Content(phr)</u>	<u>E_0 (MPa)</u>	<u>σ_B (MPa)</u>	<u>ϵ_B (%)</u>
1.0	1.73	1.70	648
1.5	1.99	2.03	572
2.0	2.10	2.21	473
5.0	2.79	2.71	194
10.0	3.82	3.39	147

Note:

 E_0 = Initial Elastic Modulus σ_B = Tensile Strength ϵ_B = Elongation - at - Break

Table E.4 Physical Properties of WTC-NR Vulcanizates

Sulphur Loading = 2.5 phr.		Cured at 160°C, 4.5 min.		
ϕ_{RR}	Property	E_0 (MPa)	σ_B (MPa)	ϵ_B (%)
0		2.69	16.82	666
20		3.23	11.84	546
50		2.81	8.68	441

Sulphur Loading = 10.0 phr.		Cured at 140°C, 15 min.		
ϕ_{RR}	Property	E_0 (MPa)	σ_B (MPa)	ϵ_B (%)
20		3.51	3.13	119
50		4.96	4.96	159

Note: A complete set of the WTC-NR series of mixes has not been evaluated.

Table E.5 Data for Mooney-Rivlin and Inverse Langevin Function Plots
for WTC-SBR Vulcanizates

Sulphur Loading = 1.0 phr

$\phi_{RR} = 0$ phr

λ	σ (MPa)	$(1-\lambda^{-1})\sigma^{-1}(10^{-7}\text{Pa}^{-1})$	$\sigma/2(\lambda-\lambda^{-2})(10^5\text{Pa})$
1.2	2.30	7.25	2.28
1.5	3.15	10.58	1.49
2.0	4.25	11.76	1.22
3.0	4.95	13.47	0.36
4.0	5.53	13.56	0.70
5.0	6.24	12.82	0.63
6.0	6.94	12.01	0.58
7.0	7.65	11.20	0.55
8.0	8.76	9.99	0.55
8.77(λ_B)	9.98(σ_B)	8.88	0.57

$\phi_{RR} = 20$ phr

λ	σ (MPa)	$(1-\lambda^{-1})\sigma^{-1}(10^{-7}\text{Pa}^{-1})$	$\sigma/2(\lambda-\lambda^{-2})(10^5\text{Pa})$
1.2	1.88	8.87	1.86
1.5	3.90	8.55	1.85
2.0	5.12	9.77	1.47
3.0	6.47	10.30	1.12
4.0	8.12	9.24	1.03
4.5	9.12	8.53	1.02
5.0	10.12	7.91	1.02
6.0	12.59	6.62	1.06
7.0	15.06	5.69	1.08
7.77(λ_B)	16.55(σ_B)	5.26	1.07

$\phi_{RR} = 50$ phr

λ	σ (MPa)	$(1-\lambda^{-1})\sigma^{-1}(10^{-7}\text{Pa}^{-1})$	$\sigma/2(\lambda-\lambda^{-2})(10^5\text{Pa})$
1.25	2.73	7.34	2.24
1.5	4.53	7.36	2.15
2.0	5.84	8.56	1.67
3.0	8.08	8.25	1.40
3.5	9.30	7.68	1.36
4.0	10.56	7.10	1.34
5.0	13.04	6.13	1.32
6.0	15.39	5.41	1.26
7.0	17.01	5.04	1.22
7.48(λ_B)	17.00(σ_B)	5.10	1.14

Sulphur Loading = 2.0 phr

$$\phi_{RR} = 0 \text{ phr}$$

λ	σ (MPa)	$(1-\lambda^{-1})\sigma^{-1}(10^{-7}\text{Pa})^{-1}$	$\sigma/2(\lambda-\lambda^{-2})(10^5\text{Pa})$
1.2	1.82	9.16	1.78
1.5	3.23	10.32	1.52
2.0	4.22	11.85	1.21
3.0	5.04	13.23	0.87
4.0	5.75	13.04	0.73
5.0	6.45	12.40	0.65
6.0	7.39	11.28	0.62
6.5	7.86	11.77	0.61
7.0	8.21	10.44	0.59
$7.54(\lambda_B)$	$8.86(\sigma_B)$	9.79	0.59

$$\phi_{RR} = 20 \text{ phr}$$

λ	σ (MPa)	$(1-\lambda^{-1})\sigma^{-1}(10^{-7}\text{Pa})^{-1}$	$\sigma/2(\lambda-\lambda^{-2})(10^5\text{Pa})$
1.2	2.49	6.69	2.46
1.5	4.49	7.42	2.13
2.0	5.92	8.45	1.69
3.0	8.13	8.20	1.41
4.0	10.60	7.08	1.35
4.5	11.96	6.50	1.34
5.0	13.70	5.84	1.38
$5.60(\lambda_B)$	$15.26(\sigma_B)$	5.38	1.37

$$\phi_{RR} = 50 \text{ phr}$$

λ	σ (MPa)	$(1-\lambda^{-1})\sigma^{-1}(10^{-7}\text{Pa})^{-1}$	$\sigma/2(\lambda-\lambda^{-2})(10^5\text{Pa})$
1.2	3.29	5.07	3.23
1.5	5.59	5.96	2.64
2.0	7.77	6.44	2.22
3.0	11.80	5.65	2.04
3.5	13.92	5.13	2.04
4.0	16.20	4.63	2.06
5.0	20.10	3.98	2.03
$5.73(\lambda_B)$	$22.10(\sigma_B)$	3.74	1.94

Sulphur Loading = 5.0 phr

$\phi_{RR} = 0$ phr

λ	σ (MPa)	$(1-\lambda^{-1})\sigma^{-1}(10^{-7}\text{Pa})^{-1}$	$\sigma/2(\lambda-\lambda^{-2})(10^5\text{Pa})$
1.125	1.73	6.44	2.58
1.25	3.24	6.17	2.66
1.5	5.11	6.52	2.42
2.0	7.11	7.03	2.03
3.0	9.72	6.86	1.68
3.5	10.66	6.70	1.56
$3.93(\lambda_B)$	$12.08(\sigma_B)$	6.17	1.57

$\phi_{RR} = 20$ phr

1.125	3.13	3.55	4.68
1.25	5.50	3.64	4.51
1.5	8.61	3.87	4.08
2.0	12.80	3.91	3.66
2.5	16.90	3.55	3.61
$2.87(\lambda_B)$	$19.11(\sigma_B)$	3.41	3.48

$\phi_{RR} = 50$ phr

1.125	3.56	3.12	5.32
1.25	6.30	3.17	5.17
1.5	10.13	3.29	4.80
2.0	16.09	3.11	4.60
2.5	22.50	2.67	4.81
$2.94(\lambda_B)$	$27.11(\sigma_B)$	2.43	4.80

Sulphur Loading = 10.0 phr

<u>λ</u>	<u>σ (MPa)</u>	<u>$(1-\lambda^{-1})\sigma^{-1}(10^{-7}\text{Pa}^{-1})$</u>	<u>$\sigma/2(\lambda-\lambda^{-2})(10^5\text{Pa})$</u>
<u>$\phi_{\text{RR}} = 0$ phr</u>			
1.1	2.14	4.25	3.92
1.25	5.40	3.70	4.43
1.5	8.53	3.91	4.05
2.0	13.48	3.71	3.85
2.94(λ_{B})	19.14(σ_{B})	3.45	3.39
<u>$\phi_{\text{RR}} = 20$ phr</u>			
1.1	3.15	2.87	5.76
1.25	6.46	3.08	5.30
1.5	11.23	2.65	5.32
2.0	18.67	3.03	5.34
2.26(λ_{B})	22.35(σ_{B})	2.49	5.42
<u>$\phi_{\text{RR}} = 50$ phr</u>			
1.1	4.54	2.00	8.30
1.25	8.54	2.37	6.93
1.5	13.90	2.40	6.59
2.0	24.00	2.08	6.36
2.47(λ_{B})	33.90(σ_{B})	1.76	7.35

Table E.6 Data for Mooney-Rivlin and Inverse Langevin Function Plots
for WTC-NR Vulcanizates

Sulphur Loading = 2.5 phr

λ	σ (MPa)	$(1-\lambda^{-1})\sigma^{-1}(10^{-7}\text{Pa}^{-1})$	$\sigma/2(\lambda-\lambda^{-2})(10^5\text{Pa})$
$\phi_{RR} = 0$ phr			
1.1	0.19	4.80	3.46
1.2	0.36	4.67	3.53
1.5	0.68	4.88	3.24
2.0	1.05	4.76	3.00
2.5	1.38	4.34	2.95
3.0	1.74	3.82	3.02
4.0	2.59	2.90	3.29
5.0	3.97	2.02	4.00
6.0	6.85	1.22	5.73
7.0	12.27	0.70	8.79
7.66(λ_B)	16.82(σ_B)	0.52	11.01

$\phi_{RR} = 20$ phr			
1.1	0.24	3.80	4.38
1.2	0.40	4.18	3.94
1.5	0.75	4.43	3.57
2.0	1.17	4.27	3.35
2.5	1.57	3.83	3.35
3.0	2.06	3.24	3.56
4.0	3.45	2.17	4.38
5.0	5.86	1.37	5.91
6.0	9.92	0.84	8.30
6.46(λ_B)	11.84(σ_B)	0.71	9.20

$$\phi_{RR} = 50 \text{ phr}$$

λ	σ (MPa)	$(1-\lambda^{-1})\sigma^{-1}\text{Pa}^{-1}$	$\sigma/2(\lambda-\lambda^{-2})(10^5\text{Pa})$
1.1	0.25	3.64	4.57
1.2	0.40	4.15	3.98
1.5	0.76	4.37	3.62
2.0	1.22	4.11	3.48
2.5	1.75	3.43	3.74
3.0	2.43	2.74	4.21
4.0	4.36	1.72	5.54
5.0	7.32	1.09	7.38
$5.41(\lambda_B)$	$8.68(\sigma_B)$	0.94	8.08

Table E.7 Mooney Constants of WTC-NR and WTC-SBR 1500 Composites

WTC - NR				
Sulphur Content /phr	ϕ_{RR} /phr	C_1 /10 ⁵ Pa	C_2 /10 ⁵ Pa	C_2/C_1
2.5	0	2.5	1.1	0.44
	20	2.5	1.7	0.68
	50	-	-	--
WTC - SBR 1500				
1.0	0	0.10	2.2	22
	20	0.40	2.2	5.5
	50	0.20	3.0	15.0
2.0	0	0.30	1.8	6.0
	20	0.40	2.5	6.3
	50	0.50	3.3	6.6
5.0	0	0.70	2.6	3.7
	20	2.20	2.8	1.3
	50	3.20	2.5	0.8
10.0	0	-	-	-
	20	-	-	-
	50	-	-	-

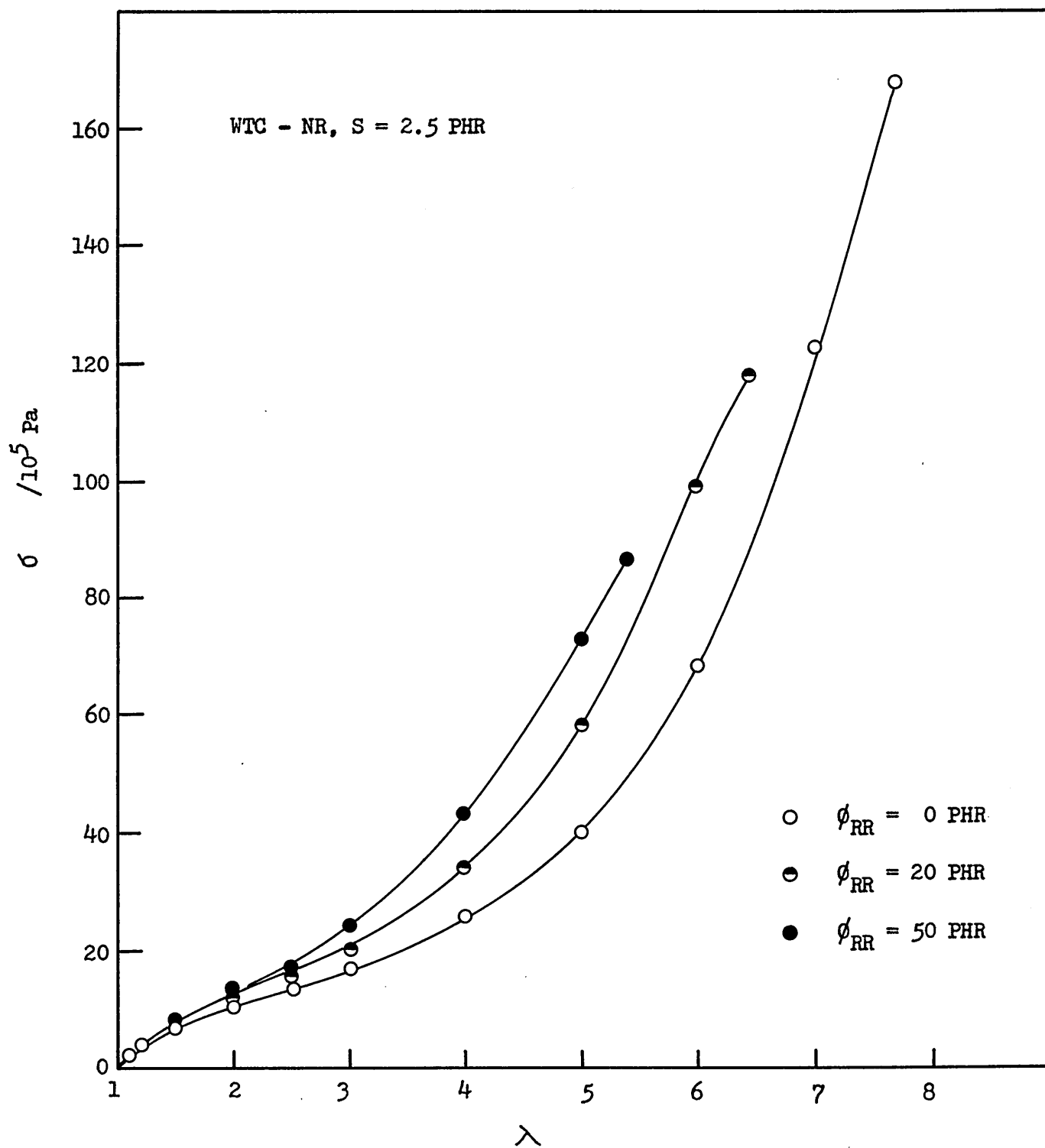


FIGURE E.1 Stress-strain diagrams for WTC-NR composites with S = 2.5 phr.

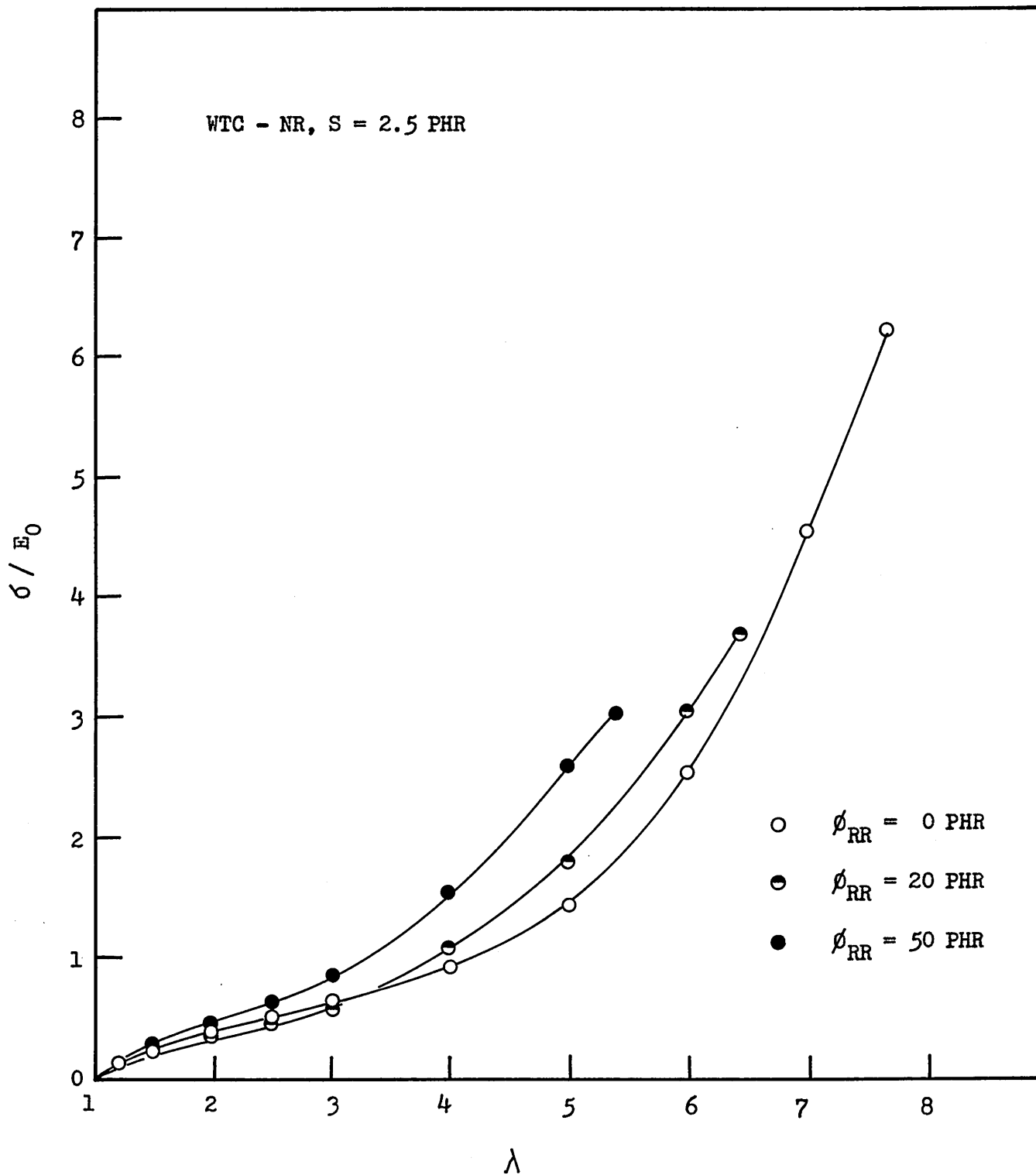


FIGURE E.2 Stress-strain diagrams for WTC-NR composites with S=2.5 phr.
Stress values have been normalised.

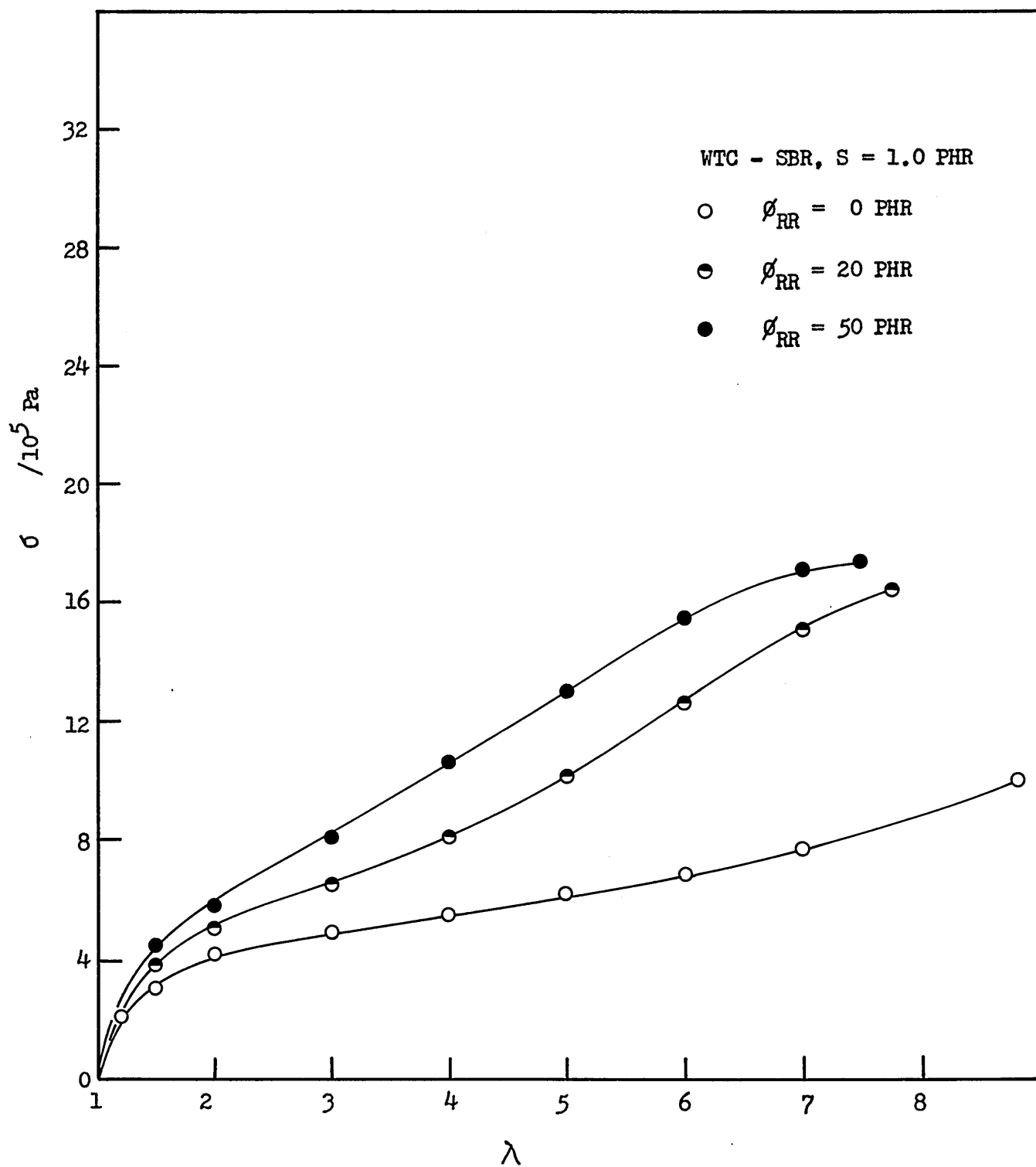


FIGURE E.3 Stress-strain diagrams for WTC-SBR with S = 1.0 phr.

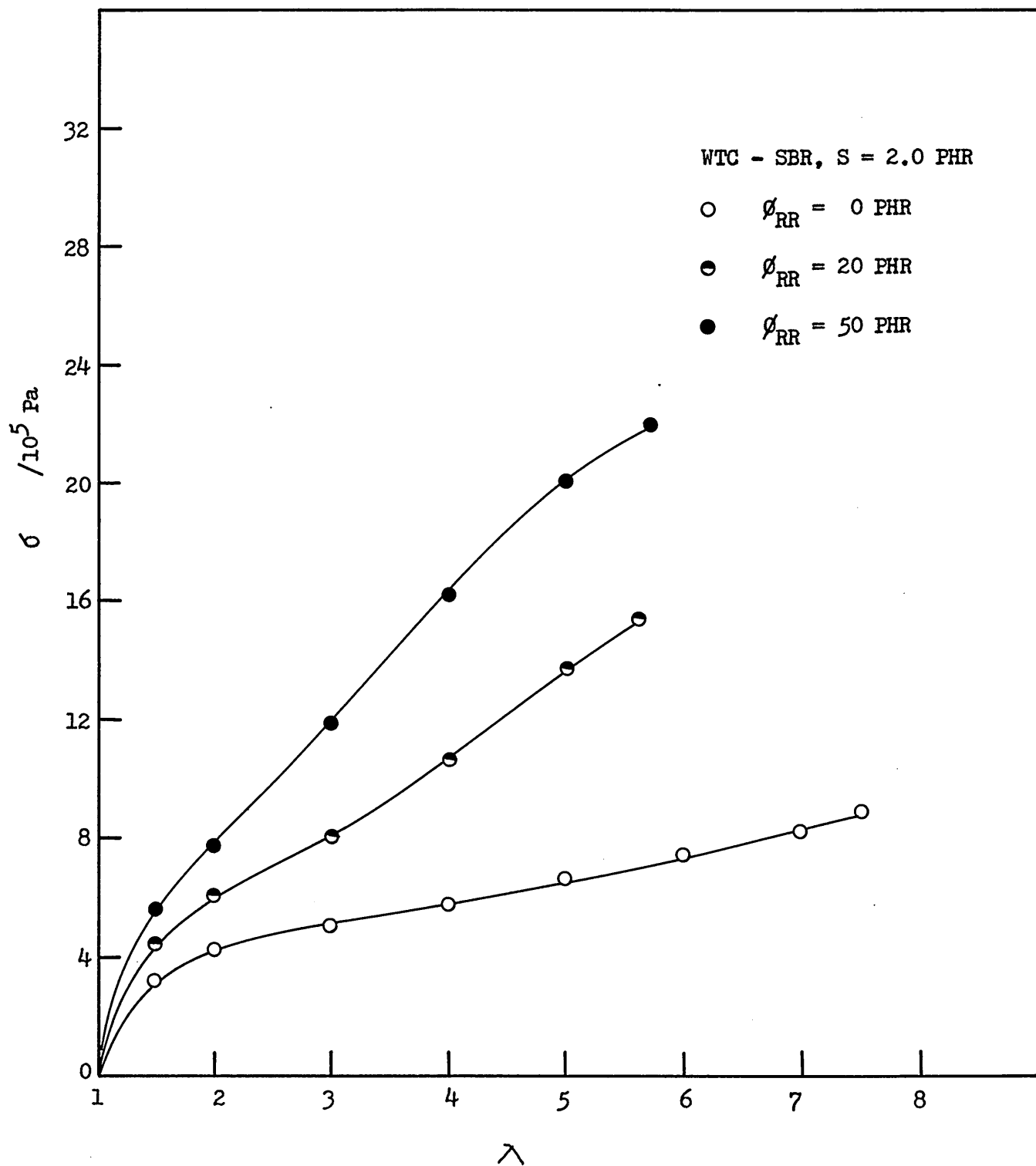


FIGURE E.4 Stress-strain diagrams for WTC-SBR composites with S=2.0 phr.

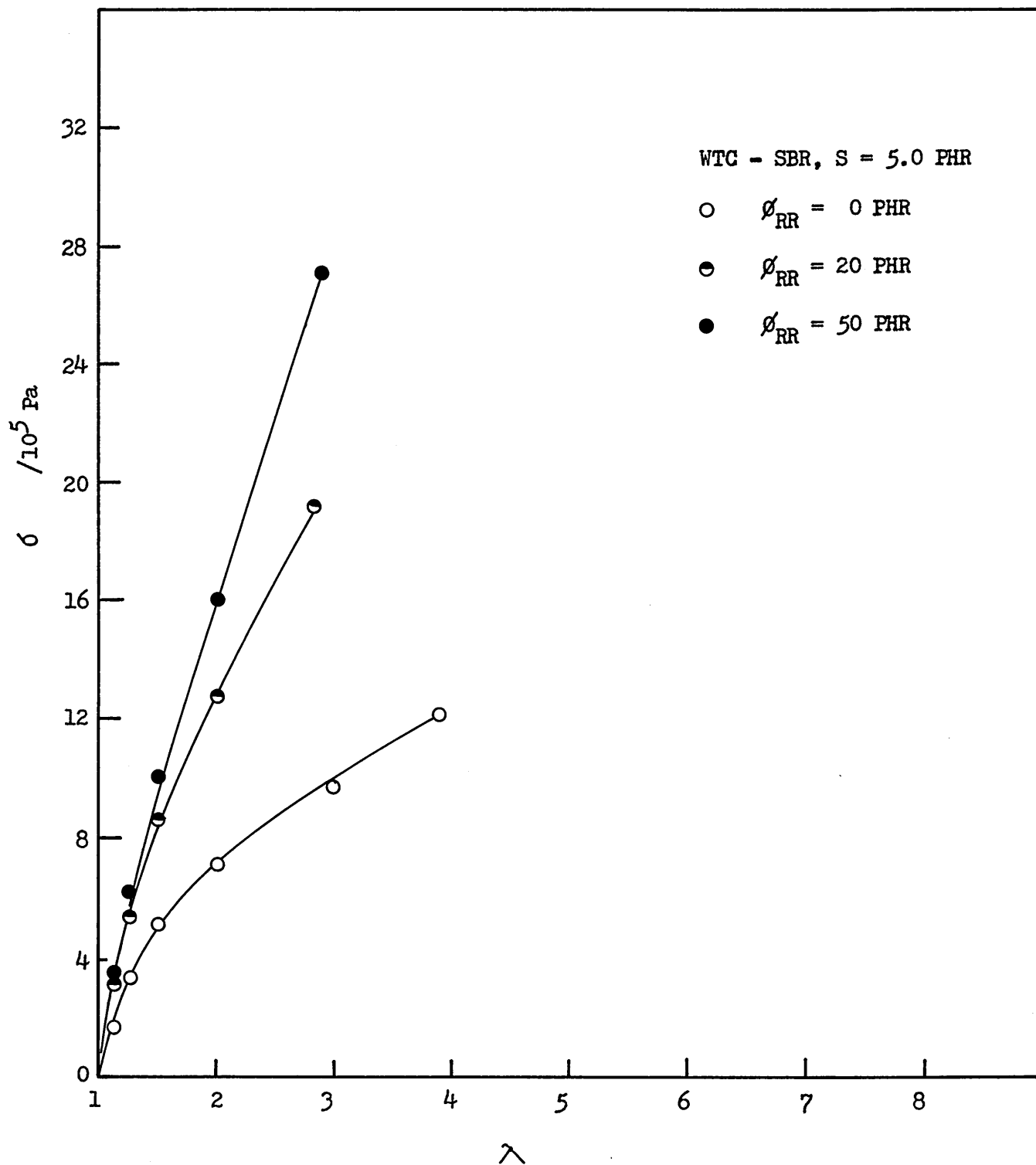


FIGURE E.5 Stress-strain diagrams for WTC-SBR composites with S=5.0 phr.

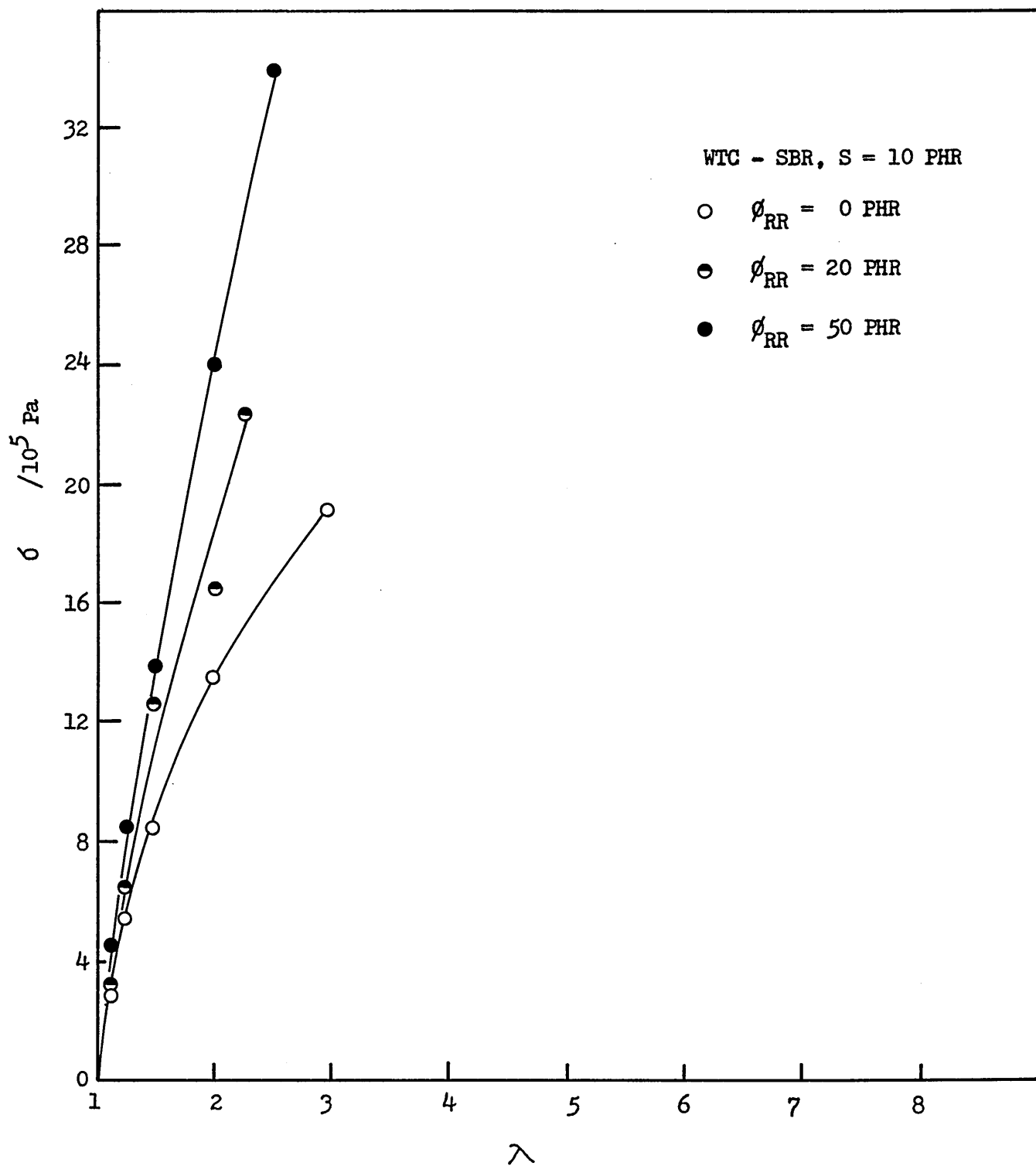


FIGURE E.6 Stress-strain diagrams for WTC-SBR composites with S=10.0 phr.

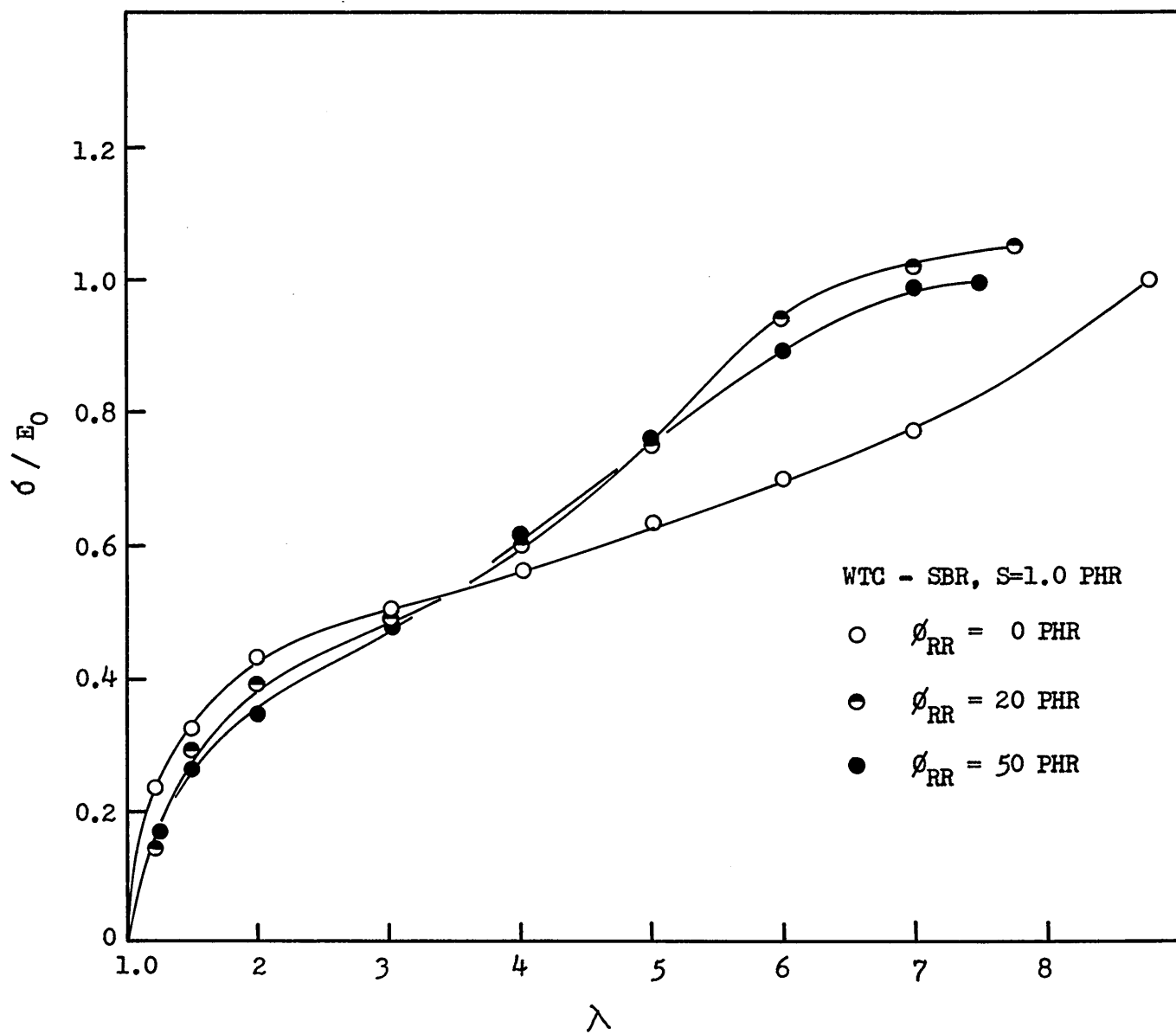


FIGURE E.7 Normalised stress-strain diagrams for WTC-SBR composites with $S = 1.0$ phr.

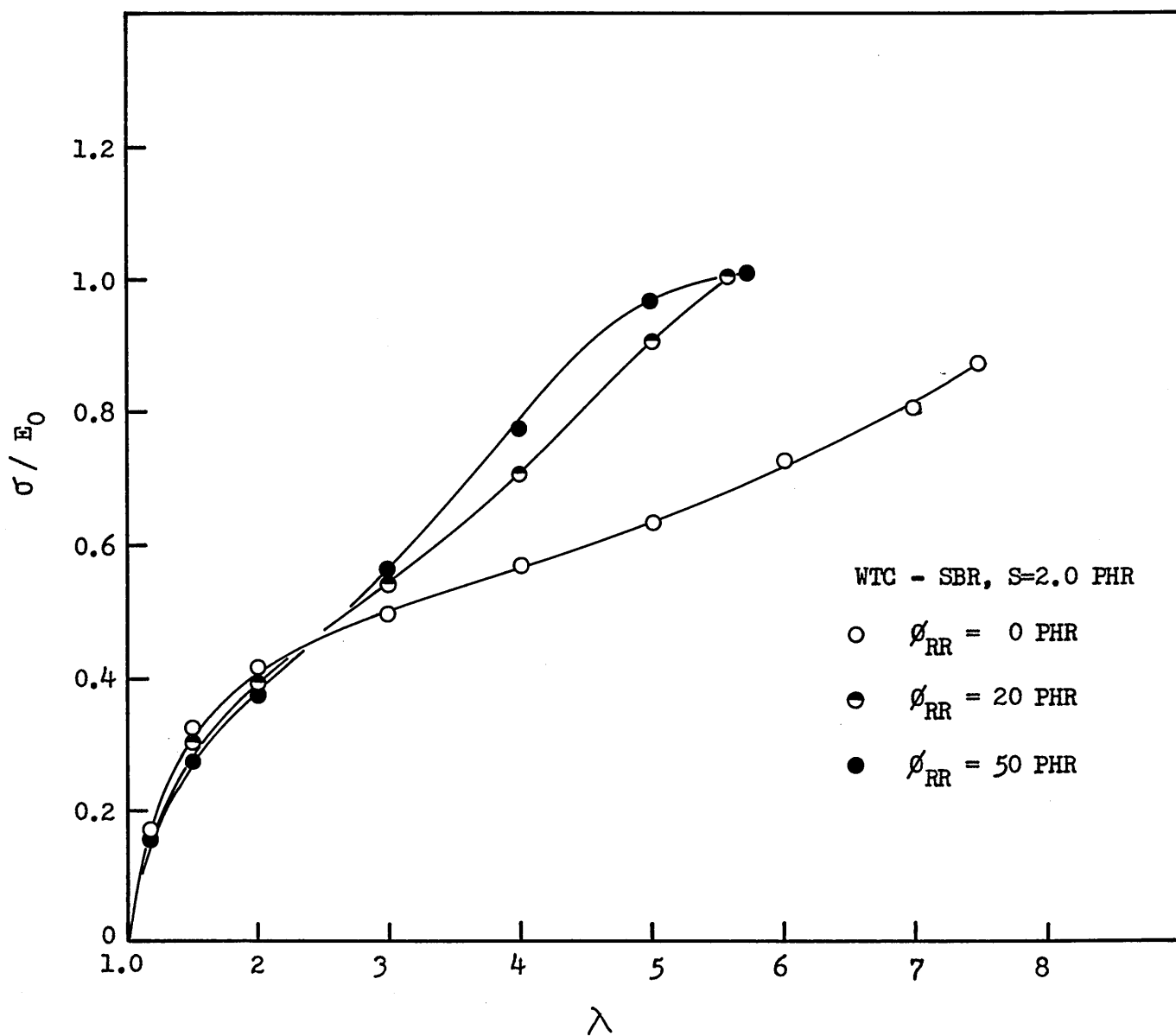


FIGURE E.8 Normalised stress-strain diagrams for WTC-SBR composites with $S = 2.0$ phr.

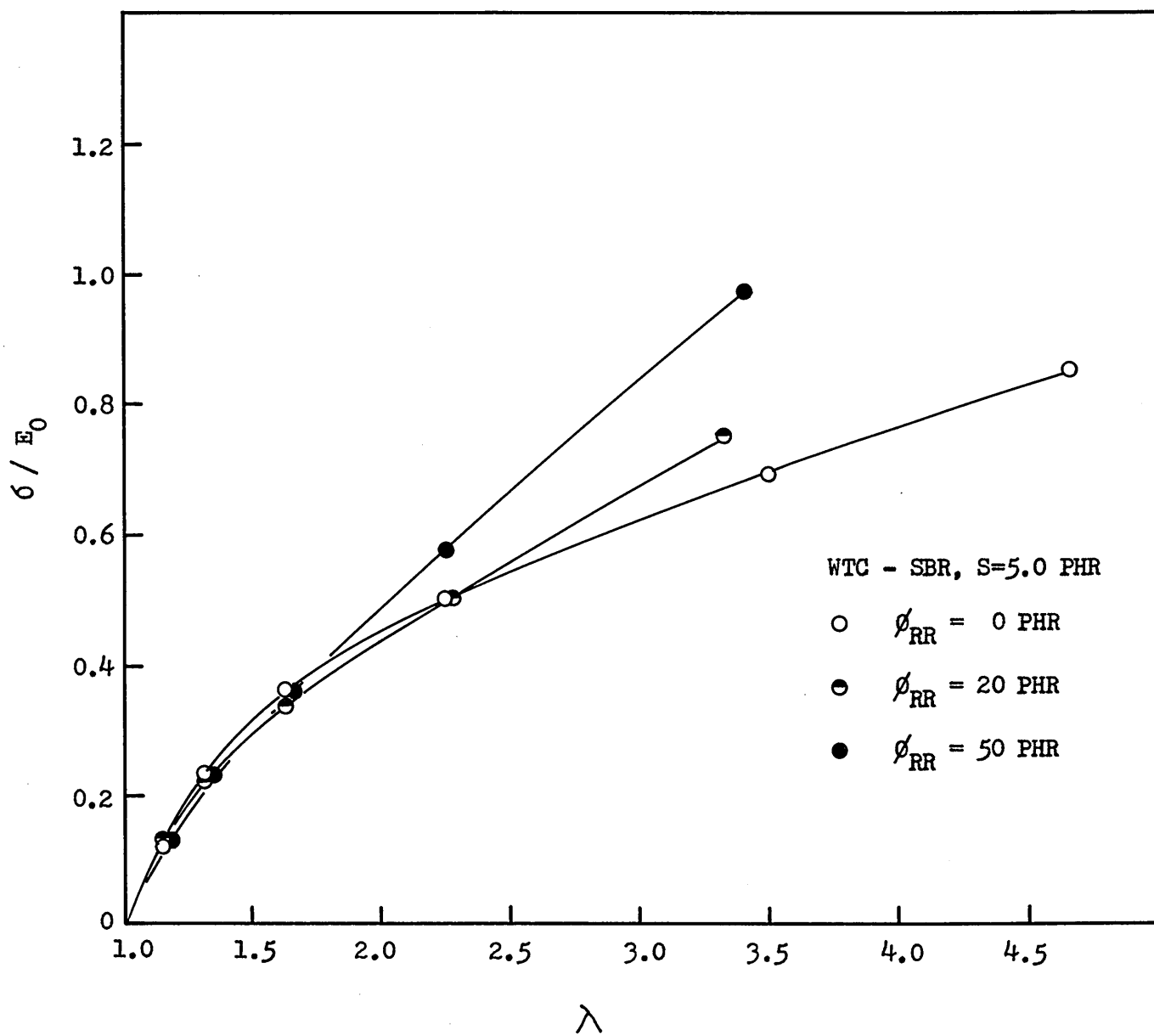


FIGURE E.9 Normalised stress-strain diagrams for WTC-SBR composites with $S = 5.0$ phr.

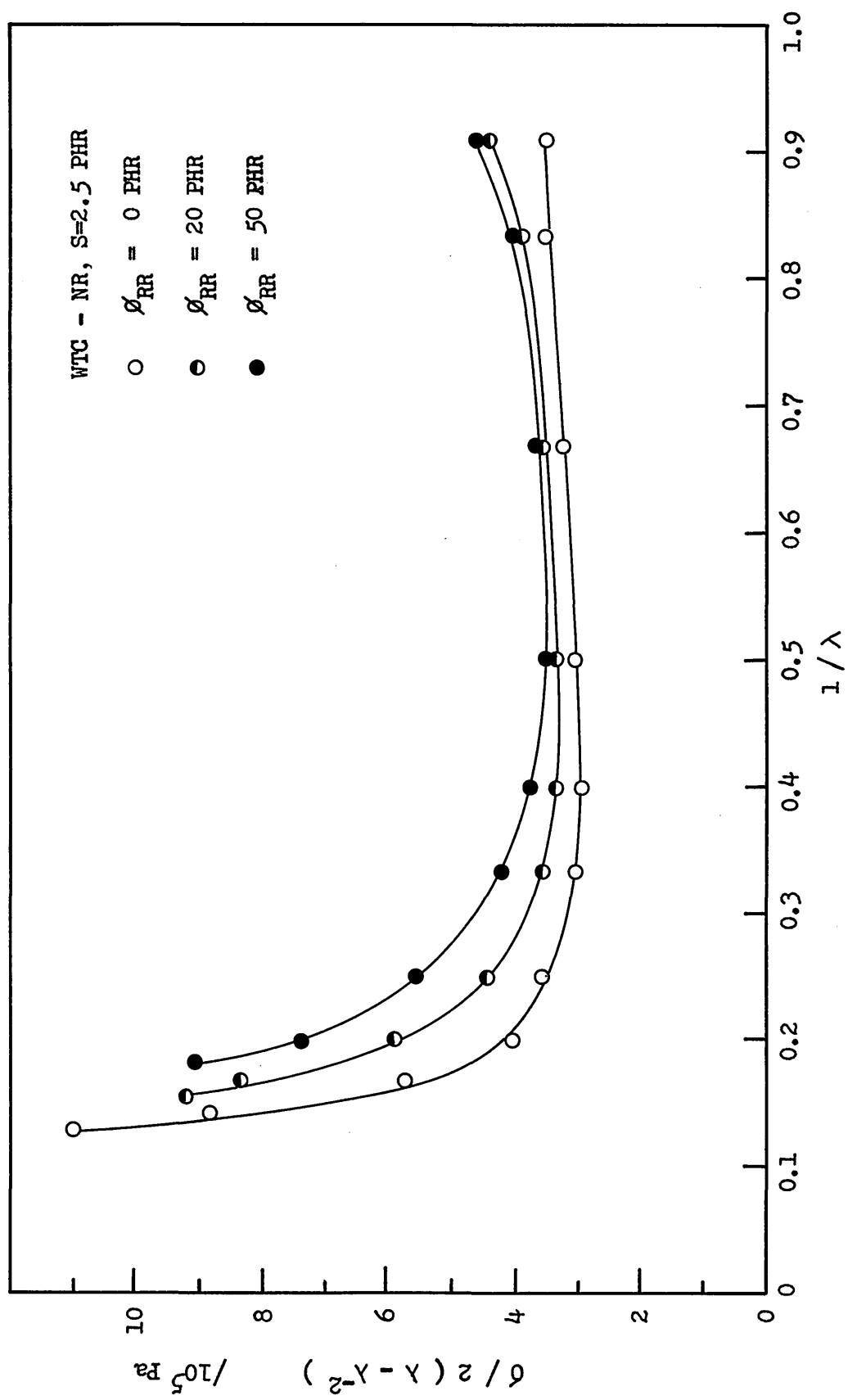


FIGURE E.10 Mooney-Rivlin plots for WTC-NR composites with $S = 2.5$ phr.

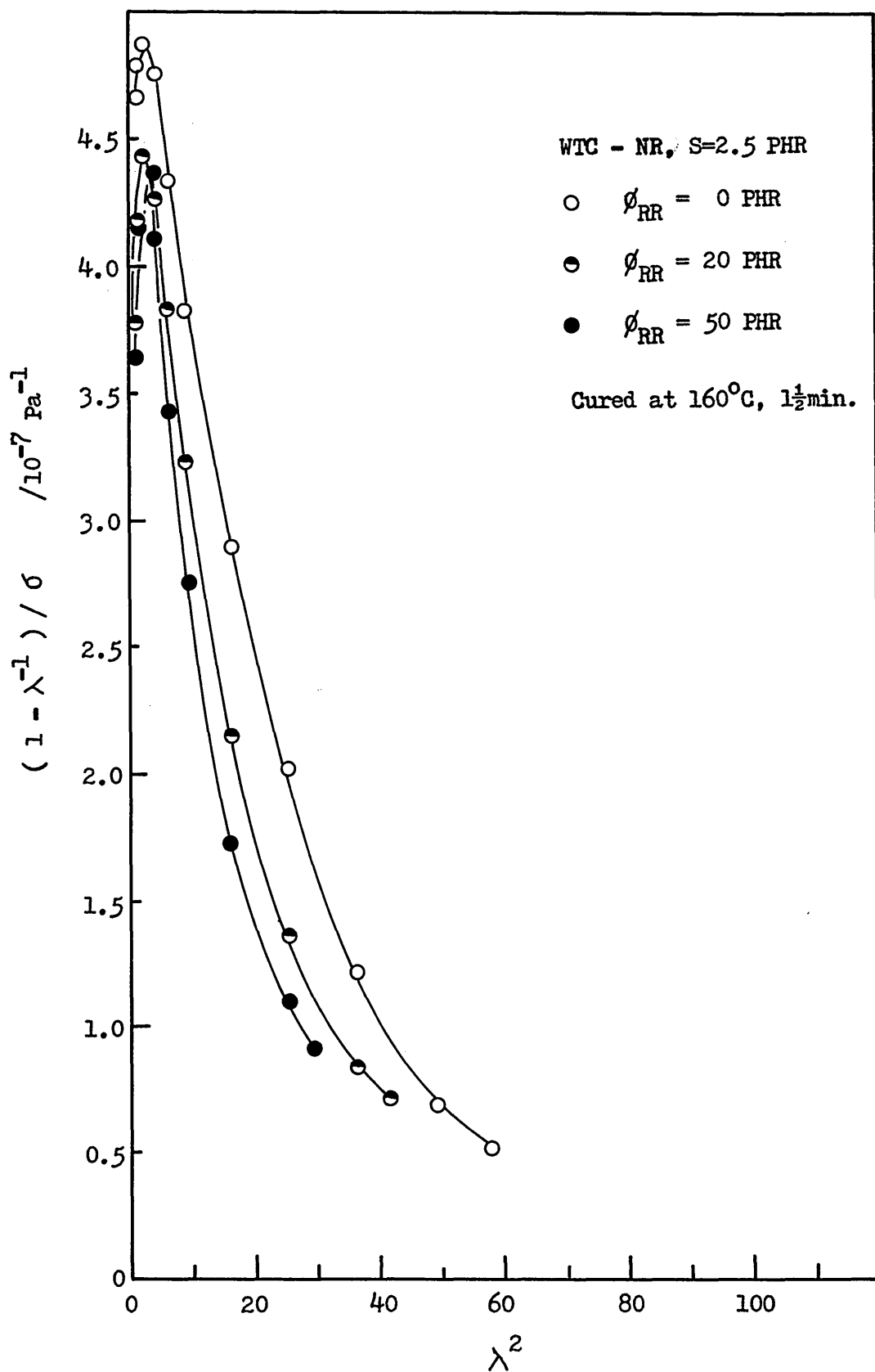


FIGURE E.11 Non-Gaussian plots for WTC-NR composites with S=2.5 phr.

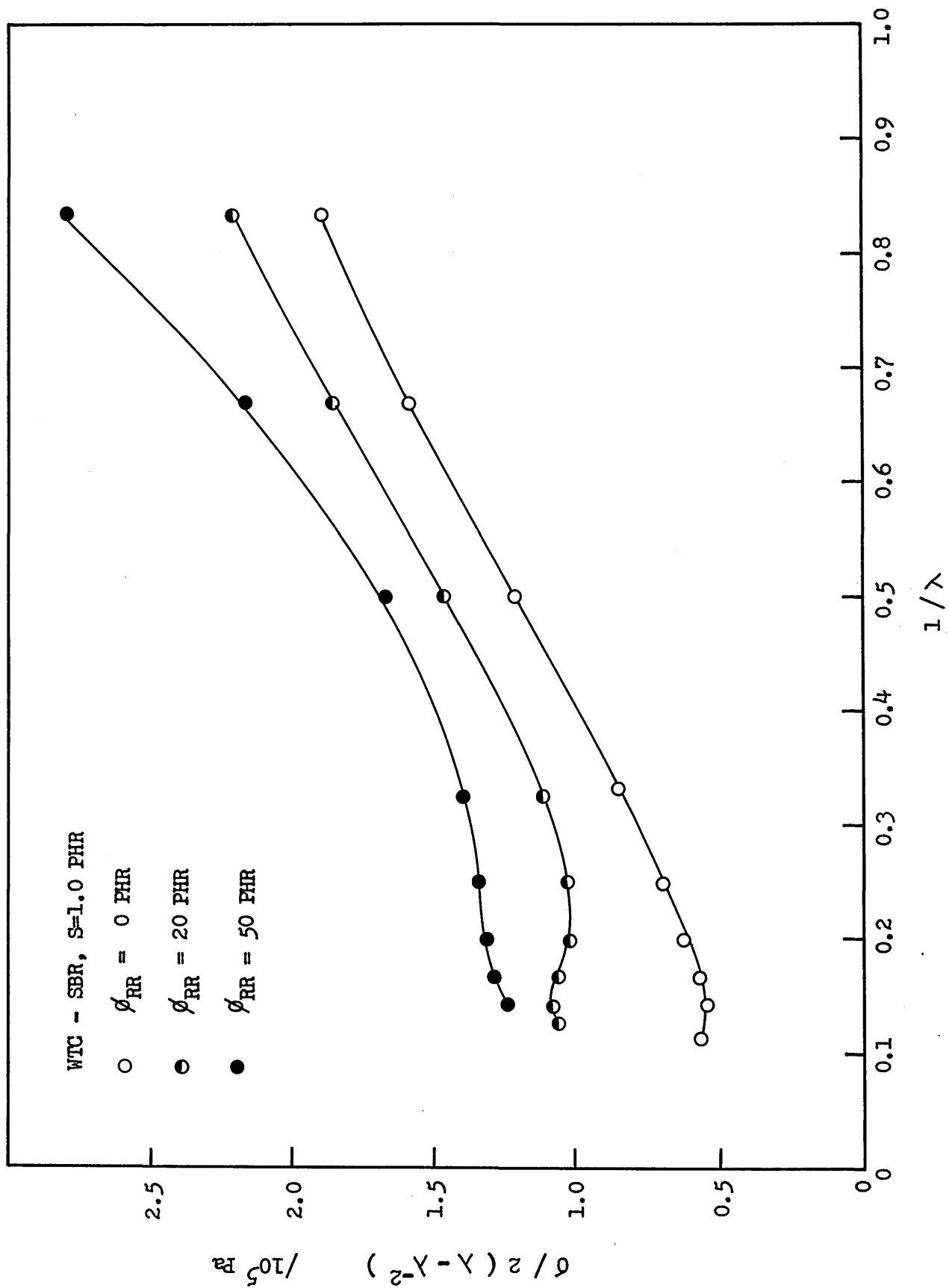


FIGURE E.12 Mooney-Rivlin plots for WTC-SBR composites with S = 1.0 phr.

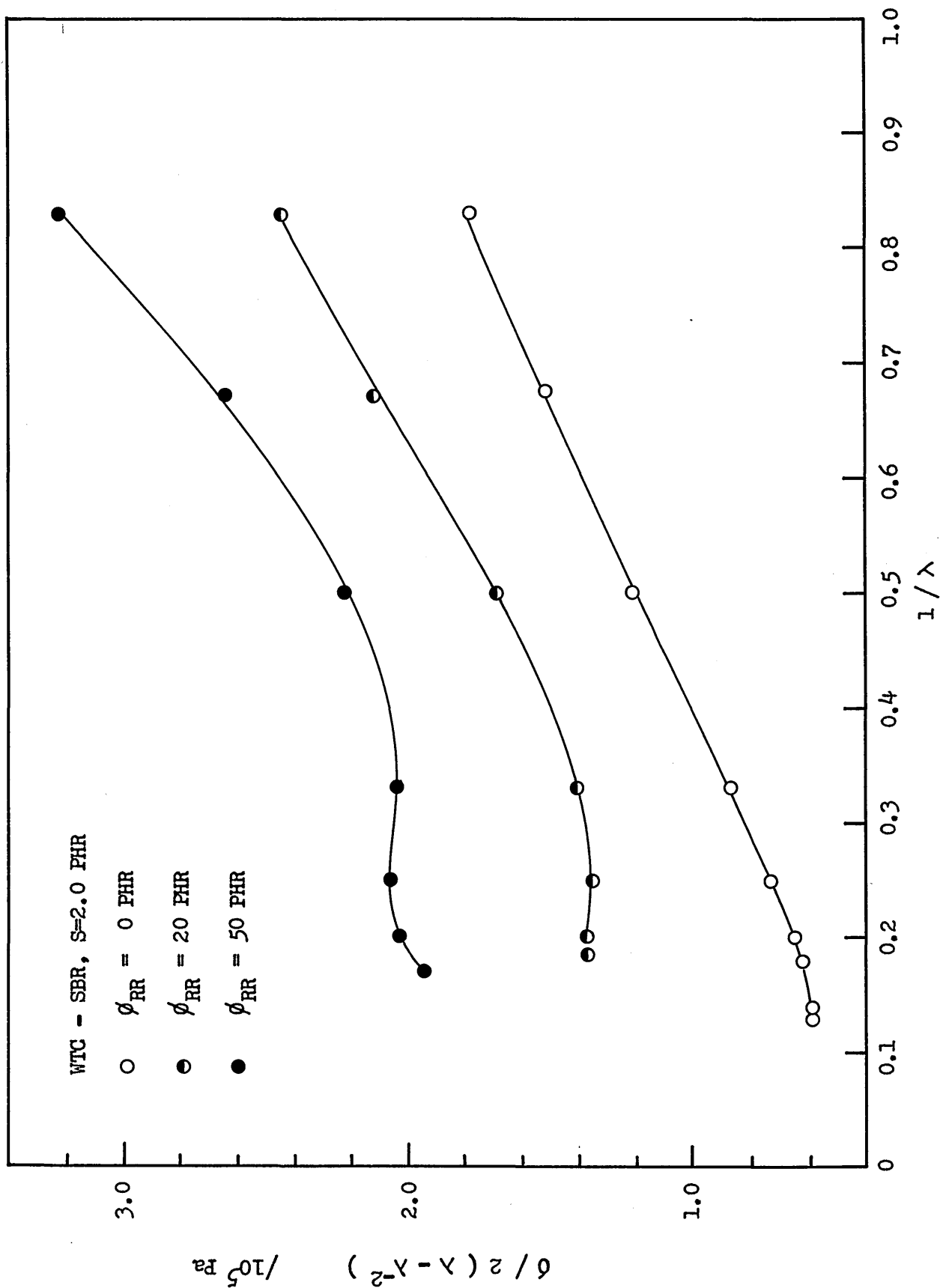


FIGURE E.13 Mooney-Rivlin plots for WTC-SBR composites with S = 2.0 phr.

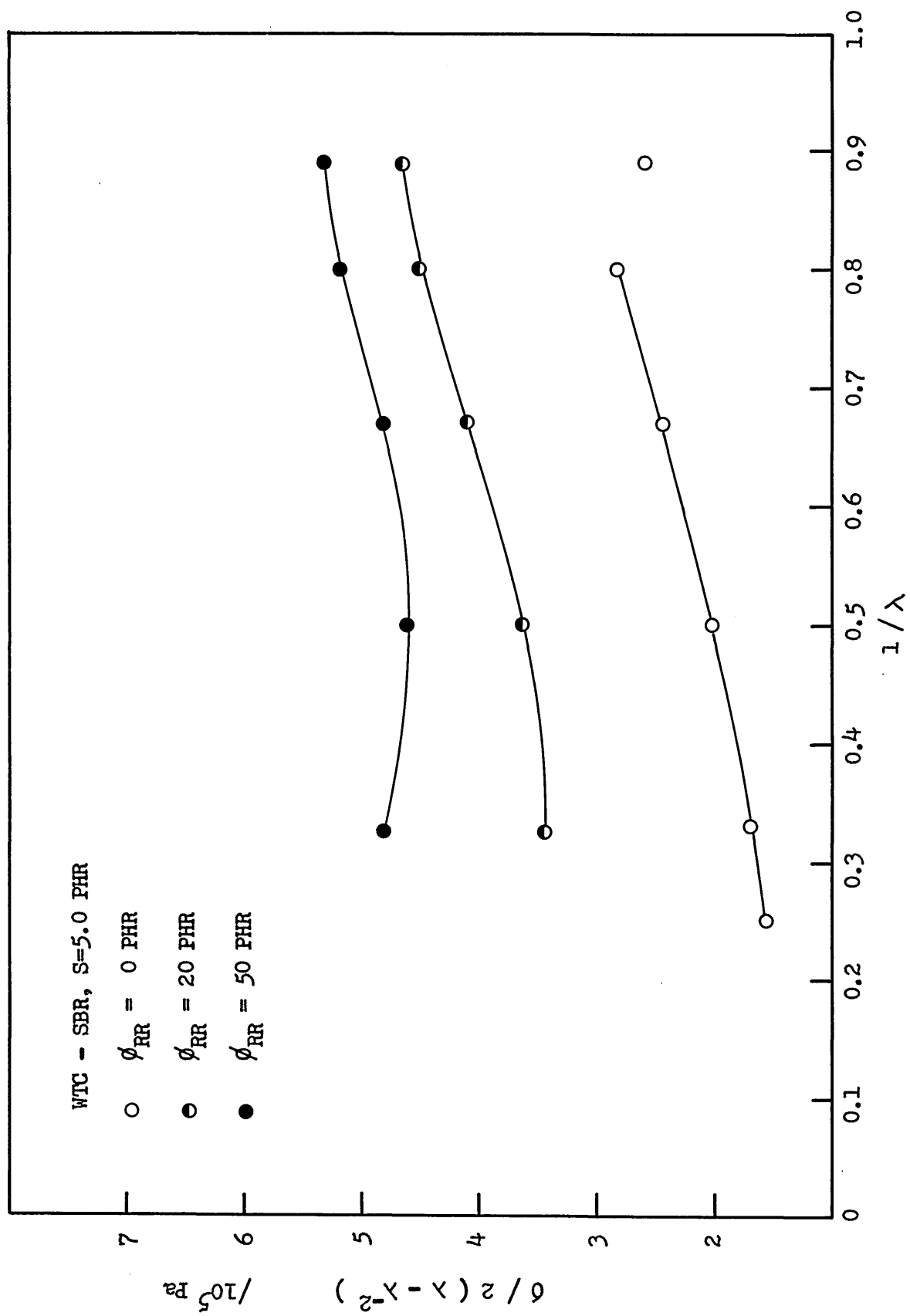


FIGURE E.14 Mooney-Rivlin plots for WTC-SBR composites with S = 5.0 phr.

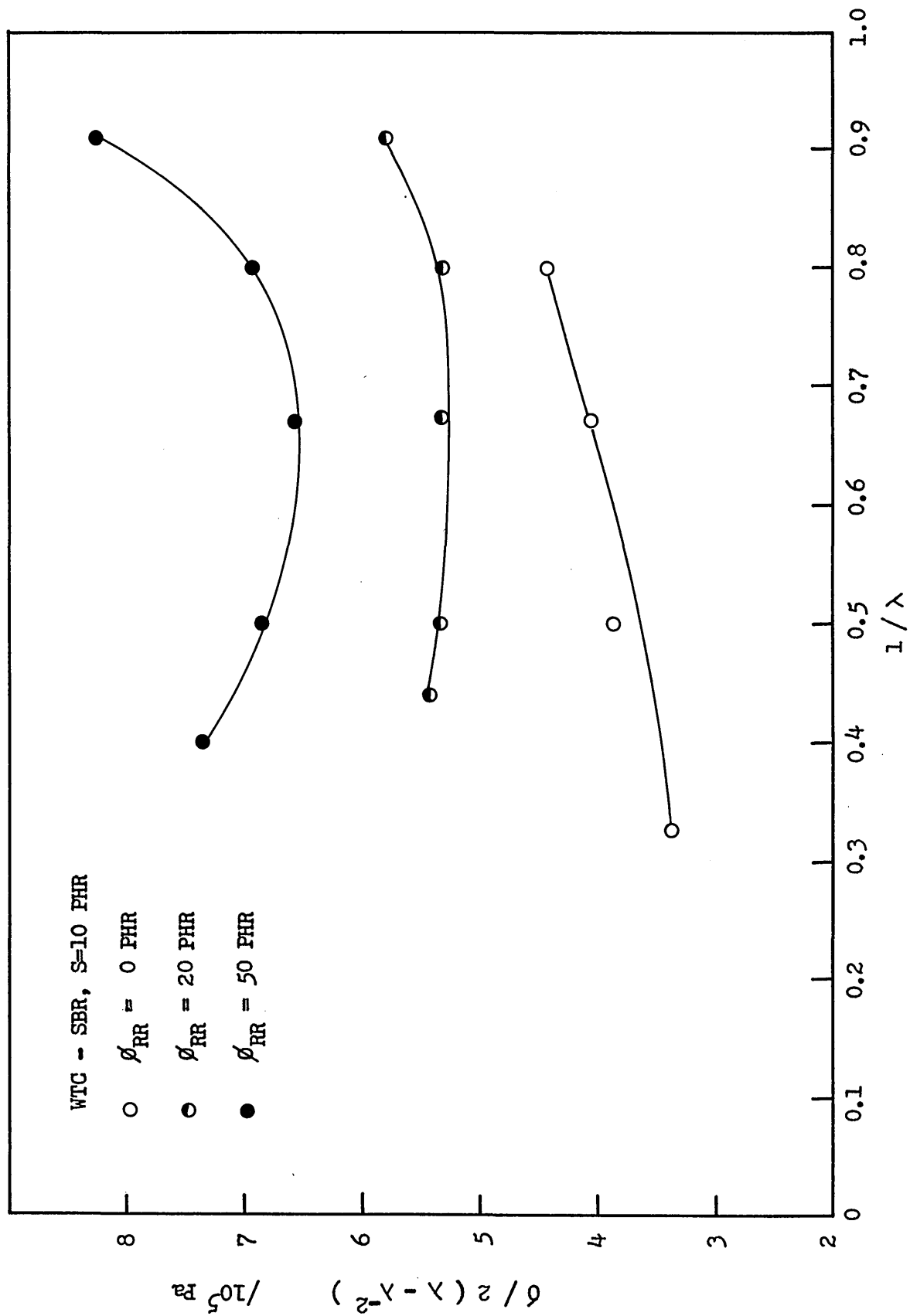


FIGURE E.15 Mooney-Rivlin plots for WTC-SBR composites with S = 10.0 phr.

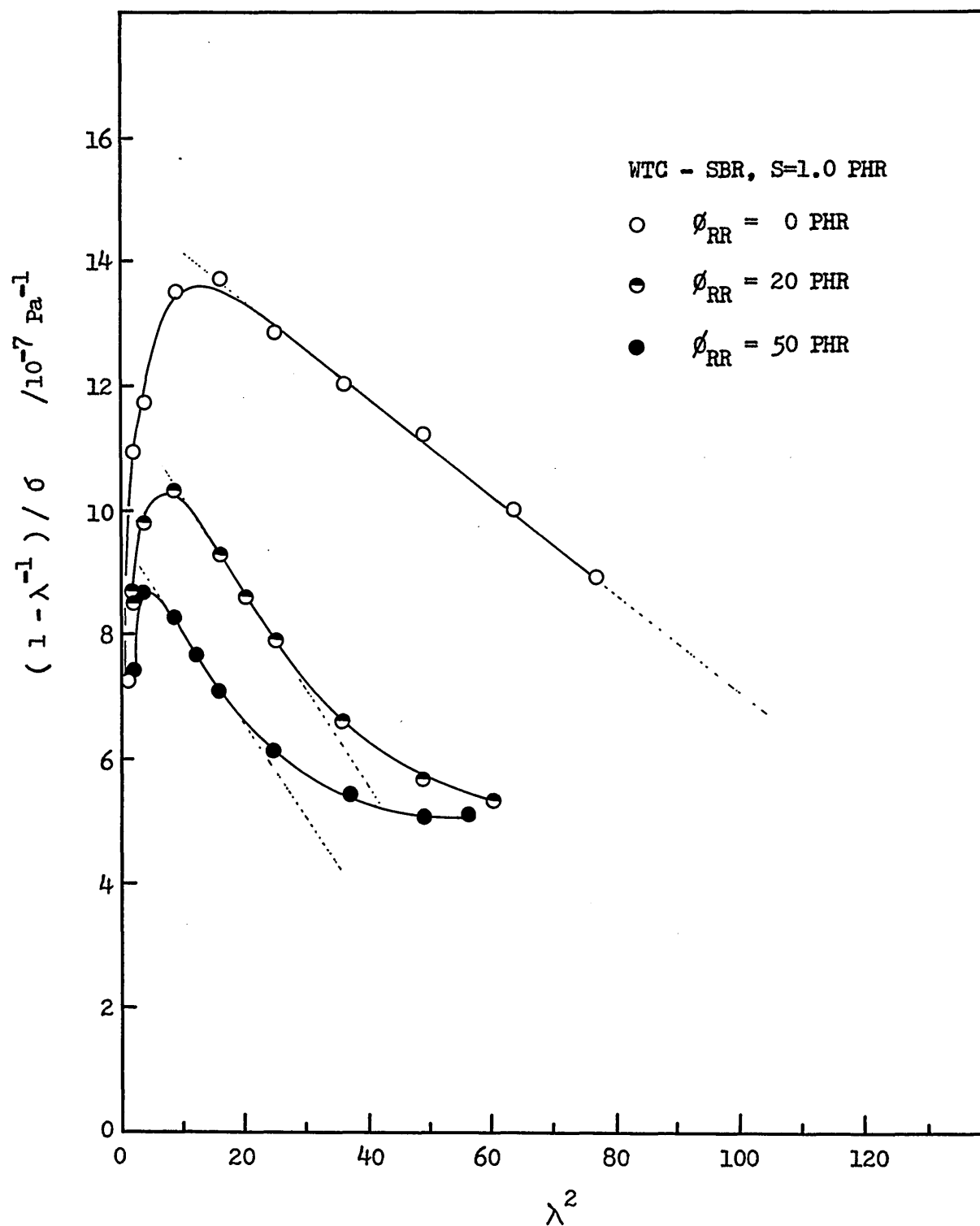


FIGURE E.16 Non-Gaussian plots for WTC-SBR composites with S=1.0 phr.

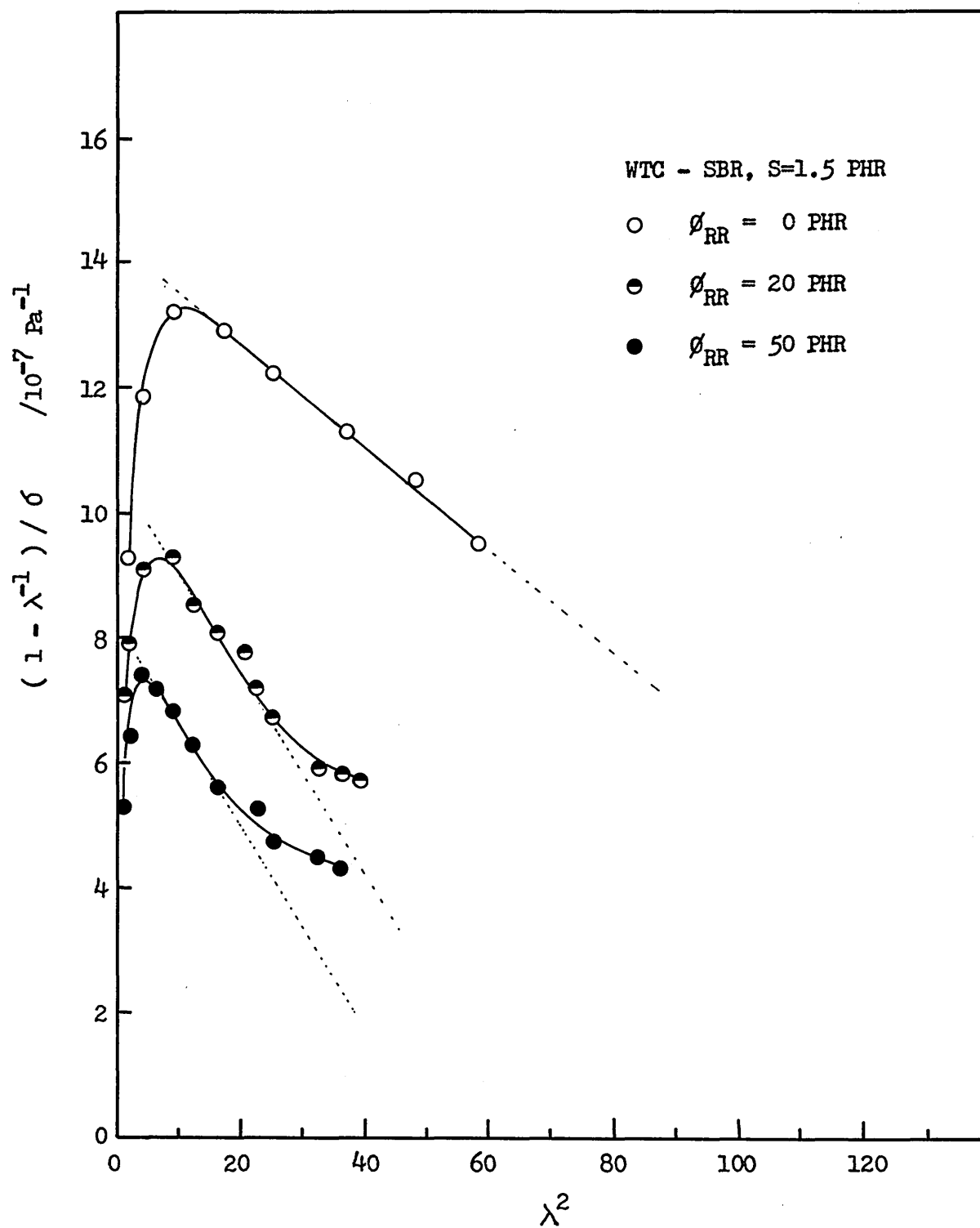


FIGURE E.17 Non-Gaussian plots for WTC-SBR composites with S=1.5 phr.

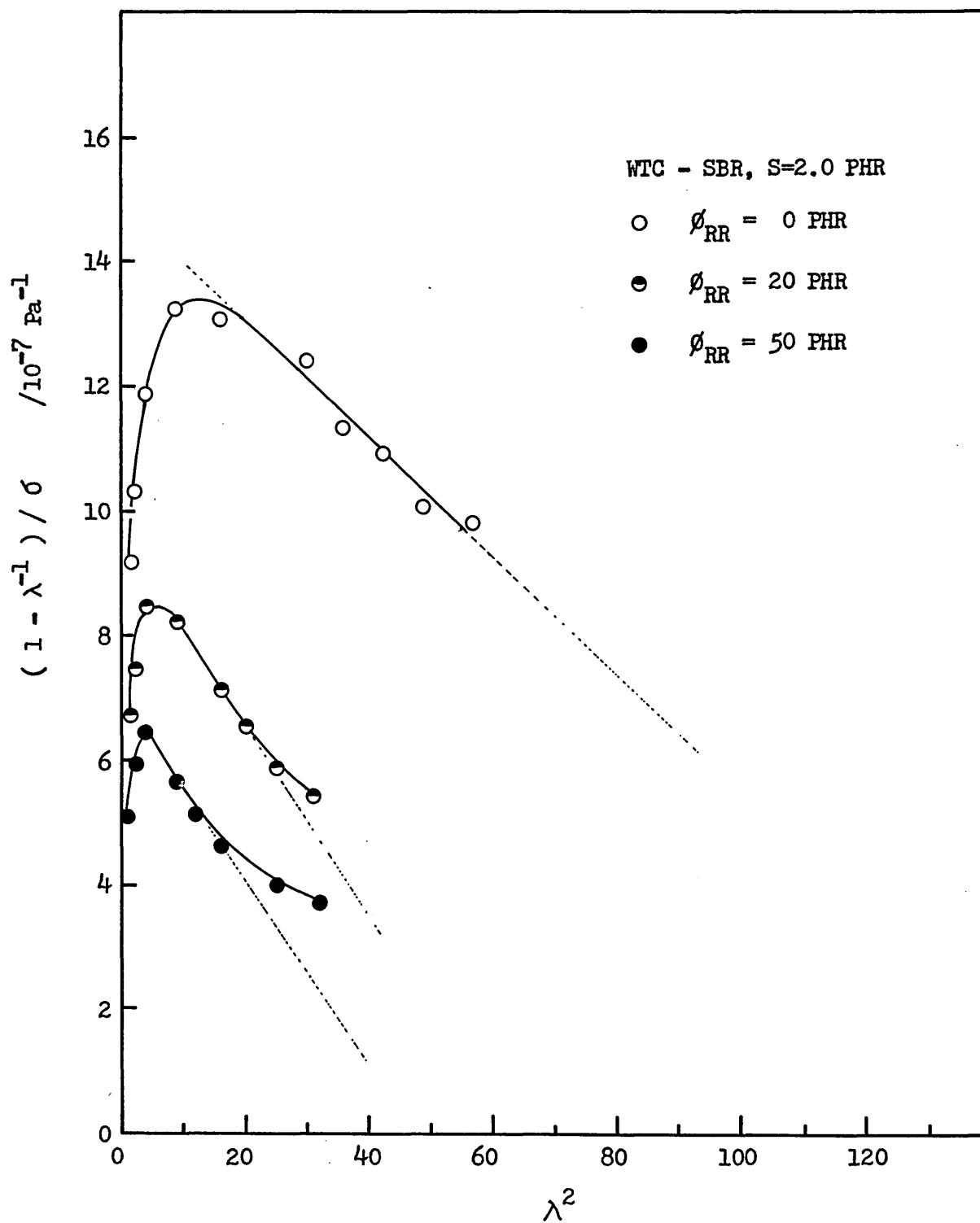


FIGURE E.18 Non-Gaussian plots for WTC-SBR composites with S=2.0 phr.

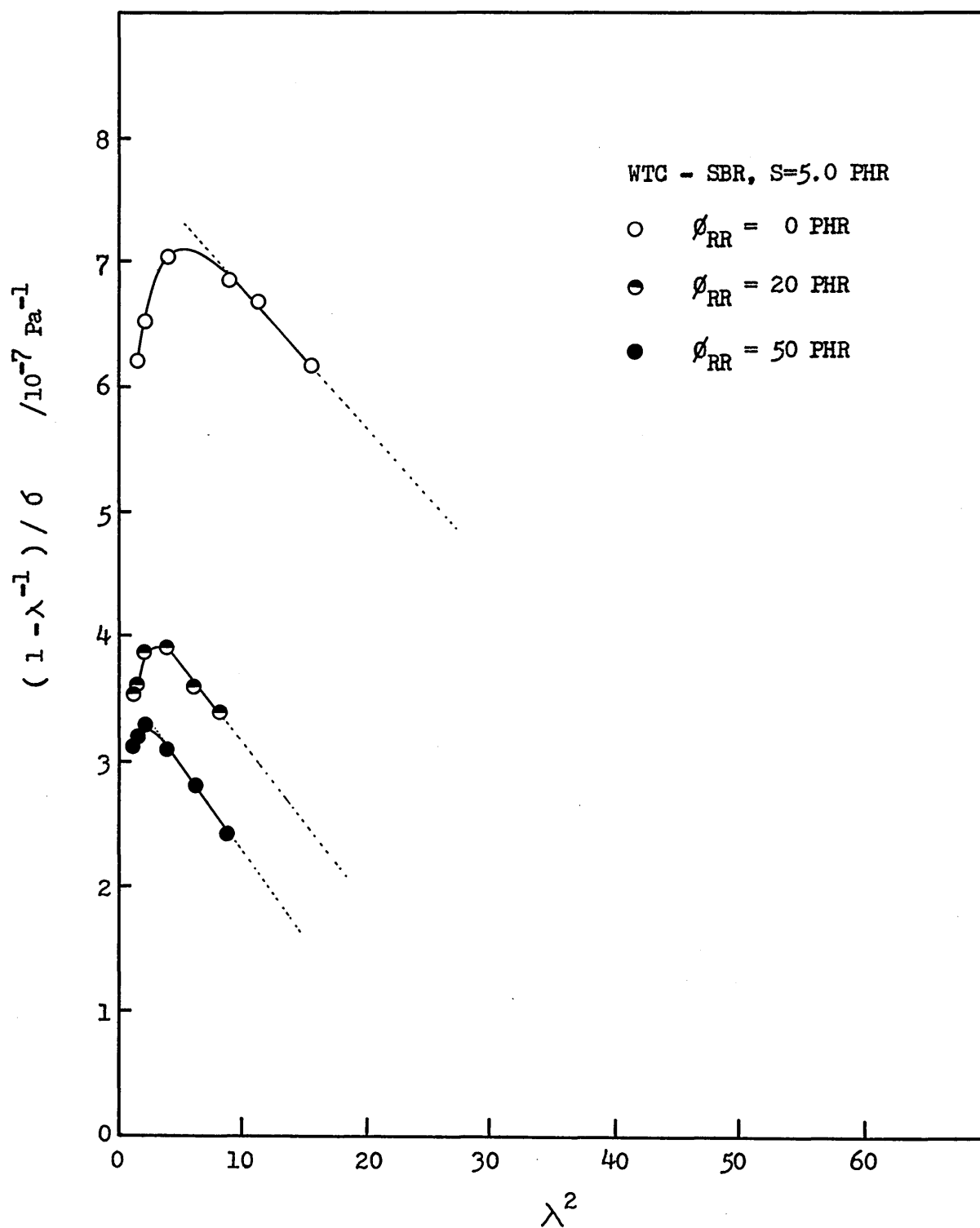


FIGURE E.19 Non-Gaussian plots for WTC-SBR composites with S=5.0 phr.

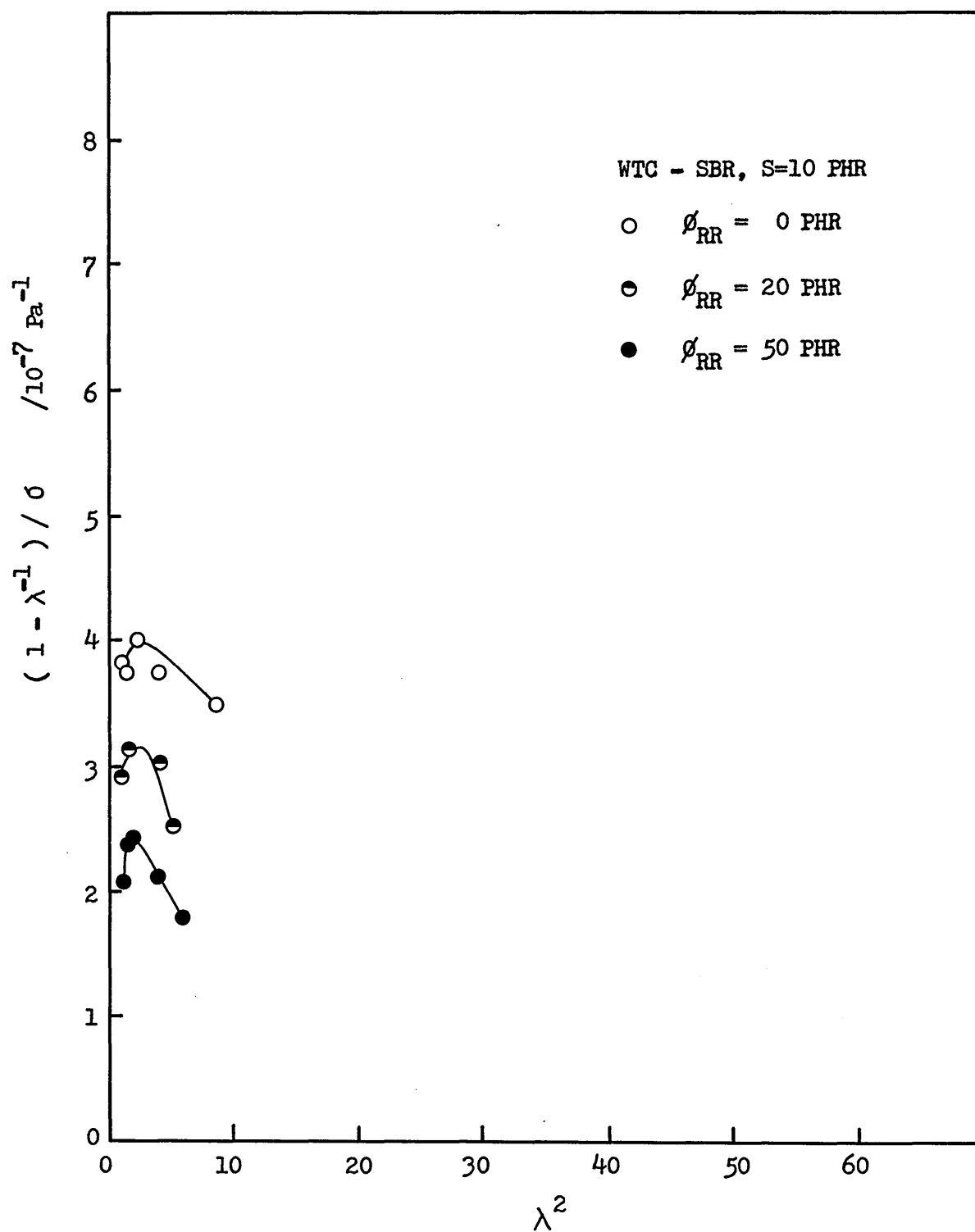


FIGURE E.20 Non-Gaussian plots for WTC-SBR composites with S=10.0 phr.

BRIEF DESCRIPTION OF SCANNING ELECTRON MICROSCOPYF.1 Electron - Solid Interactions

When a focused beam of electrons strikes a solid specimen, the electrons are either undeviated or they are scattered. The undeviated or unscattered electrons are transmitted through the specimen with (inelastic) or without (elastic) slight loss in energy. Electrons may reflect or backscatter from the surface of the specimen with little or no energy loss, or they may interact with the surface atoms to produce low energy secondary electrons. Some electrons may be absorbed by the specimen, converting their energy into heat and sometimes light which is emitted as visible fluorescence. The transference of energy from the electrons to the specimen results in the production of Auger electrons and/or X-rays. The important electron-solid interactions are illustrated in Figure F.1 below.

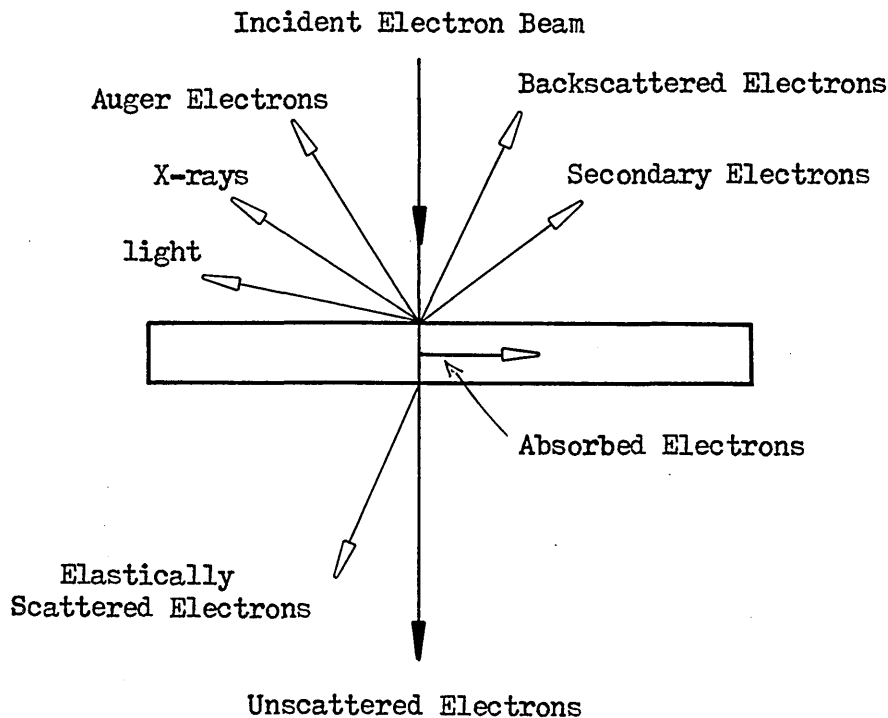


FIGURE F.1 The important interactions of an electron beam with a solid specimen.

Each of these interactions provides information about the specimen. The transmitted electrons are pertinent to conventional transmission electron microscopy (TEM) while the main interactions related to scanning electron microscopy (SEM) are those with electrons emitted from the front of the specimen.

The secondary electrons are strongly dependent on the surface topography of the specimen, hence they are used to form SEM surface images, or better known as SEM micrographs, of the specimen surfaces. The X-rays emitted form the basis for EDAX, Energy Dispersive Analysis of X-rays. The EDAX facility includes X-ray mapping, line scan and point analysis. Detailed descriptions of these and other techniques are readily found in standard texts (eg. Chandler (174), Hearle (175), Goldstein (176) and Russ (EDAX) (177,178)).

Every element in the periodical table has a very defined distribution of electrons within the atom. X-ray microanalysis is dependent upon the excitation of these electrons (such as when bombarded by a high energy electrons beam). This produces an emitted X-ray spectrum characteristic to the element concerned. The energy of this incident electron beam must be sufficiently high to ionise the atoms of the element concerned. This energy is termed the critical excitation potential, E_c , which for sulphur K_{α} emission line can be estimated by:

$$E_c = \frac{hc}{e\lambda_k} = \frac{6.6 \times 10^{-34} \times 3 \times 10^8}{1.6 \times 10^{-19} \times 5 \times 10^{-10}} \text{ V} \approx 2.48 \text{ kV}$$

where h is the Plank's constant, c is the velocity of light, e the charge on the electron and λ_k is the wavelength of the X-ray emitted.

There is a simple relationship between the frequency of the X-ray, ν (and hence its energy, $E = h\nu$), and the atomic number, Z of the element, given by

$$\nu = 0.248 (Z-1)^2 \times 10^{16}$$

Hence, measurement of the energy of the characteristic X-ray emission from an element allows the element to be identified. Conversely, by specifying a particular element to be studied, the X-ray microanalysis allows the occurrence of this element to be pinpointed. The concentration of an element, C , in a bulk sample, under a given set of operating

conditions, is proportional to the intensity of the characteristic X-ray emission:

$$C = kI$$

where I is the intensity of the X-ray and k is a constant. Therefore, the intensity of the characteristic X-ray emission, allows a method of quantifying the amount of the element concerned in the specimen. However, due to a number of other interactions occurred which affect the production and collection of X-ray, the determination of absolute values of concentration becomes very complex. This may involve using standard elements and applying several correction. ZAF correction is widely used with bulk specimens (Z for correcting atomic number effect, A for absorption effect and F for fluorescence effect).

These relationships between X-ray energy and its element, and between intensity of the X-ray and concentration of the element form the basis for X-ray microanalysis.

F.2 Specimen Preparation

Microanalysis in the SEM, in most applications, is essentially an analysis of the specimen surface. Therefore, it is necessary that the prepared surface is truly representative of the bulk of the sample. There are established methods of specimen preparation for different samples (see standard SEM texts for example Chandler (174) and Hearle (175)), some of which have been specially developed (such as those for preparing biological samples). Most methods of preparation involve treating the specimen mechanically, chemically or thermally. Each of these treatments can cause some loss or redistribution of the elements under examination, displacement or repositioning of the elements, contaminations and change the ultrastructure of the specimen.

The basic procedure for specimen preparation is relatively straight forward. Samples are cut into an appropriate size. This size is determined by the chamber of SEM. For metal specimens, samples may be obtained from rods, sheets etc. Rubber samples may be cut from tensile sheets using a sharp razor blade. These samples are then stuck to a convenient metal mount using an appropriate adhesive. For conducting samples, it is essential that there is good electrical conduction between the specimen and the mount. This can be achieved by either

using a conducting adhesive to mount the samples, or painting a good conduction line from the conducting samples to the mount using a conductive paint. These conductive glue and paint are available commercially. For non-conducting specimens, such as rubber, the samples are usually mounted on metal stud using a conducting glue. These are then coated with a thin conducting layer of carbon or metal (gold and aluminium are frequently used.) so as to provide a conducting path, and subsequently suppressing the build-up of charges and increase the electron emission. Coating of conducting layer is usually carried out by vacuum deposition technique.

Specimen preparation for some samples are, however, more complex especially the biological ones. This is due primarily to the volatile content of the specimens under vacuum conditions. Special techniques have been developed for these and other delicate specimens (see for example chapter nine of Hearle et al (175) and chapter four of Chandler (174) for a discussion).

F.3 Operating Conditions

As mentioned earlier, a number of interactions occur when a solid specimen is irradiated by a focused beam of electrons. Some of these interactions form the basis for the X-ray microanalysis and other SEM analytical techniques, other interactions may not be as useful and tend to impair the accuracy of the analysis performed. Modern scanning electron microscopes are equipped with a variety of controls that enable a wide range of operating conditions to be selected to suit a particular analysis and specimen. The main objective of optimising the operating conditions is to minimise

- i) electrostatic charging;
- ii) damage to specimen;
- iii) contamination; and
- iv) primary and secondary electron scatter

Electrostatic charging occurs with non-conducting specimens which have not been properly treated. Coating of the specimen with a thin conducting layer, such as carbon and metal, will largely eliminate this problem. However, electrostatic charging still occurs at localised regions which the coating is insufficient or the sample has detached. The detachment of part of a specimen, and hence the occurrence of

localised electrostatic charging, have been observed with specimens of loose rubber crumb.

When electrons interact inelastically with the specimen, energy is lost from the electrons to the specimen. This can result in irradiation damage and thermal damage to the specimen. Radiation crosslinking may occur in rubber samples, although such structural change to the rubber samples would not affect the study of elemental sulphur distributions.

The effect of a contamination layer on the specimen surface is to absorb low energy X-ray emerged from the specimen. It will also affect the mass thickness of the sample, hence increasing the background signal and the accuracy of the analysis. Contamination of specimen during analysis occurs when there is a poor vacuum in the specimen chamber.

As well as being absorbed by the specimen to produce X-rays, causing radiation damage and generating heat, electrons are being scattered from the surface of the specimen. These scattered electrons may strike other parts of the instrument, resulting in the generation of X-ray signals from these parts. The net effect is an increase in background signal. The extend of electron scattering depends on the specimen itself as well as the operating conditions such as electron accelerating voltage and beam current.

Some of the commonly available SEM operating condition controls are listed below:

- i) specimen angle;
- ii) position of X-ray detector from the specimen;
- iii) aperture setting of the electron beam condenser system;
- iv) spot size of the electron beam;
- v) electron beam accelerating voltage,
- and vi) filament current.

Each of these controls will affect the interactions between the solid specimen and the electron beam, and hence the result of the analysis carried out. Discussion on the effects of these operating condition controls can be found in standard text (such as Chandler (174) and Hearle et al (175)), suffice is to note here that a set of optimum conditions must be followed for all specimens in order to ensure consistency of results.

APPENDIX G

DETAIL COST DATA FOR ND, KEK-BOC PROCESS

G.1 Introduction

This Appendix shows the details of the cost data and their derivation for the Newell Dunford (ND) and KEK-BOC cryogenic grinding systems.

The whole process considered here is divided into two stages. The first stage is a primary grinding process which yields coarse crumb (see Appendix B for a discussion on primary and secondary grindings). The output from the first stage undergoes a secondary grinding stage (KEK-BOC process, see Appendix B) which converts the coarse crumb into fine crumb. Two sets of cost data are therefore required, each associated with the respective stage/process. Relatively complete set of cost data has been obtained for the ND process. The operating costs for ND process are used to estimate the operating costs of the KEK-BOC process, with the appropriate modifications. The two sets of costs data are then merged to give a single set of data for the whole process. Care has been taken so as not to double count some costs (such as administration costs and the liquid nitrogen tank rental).

The production schedule is assumed to be:

3 x 8-hour shift per day,
5 days per week,
and 47 weeks per year.

This schedule gives a $(3 \times 8 \times 5 \times 47)$ 5640 working hours per year.

The scrap rubber tyre feed is assumed to yield:

65% by weight of rubber crumb,
20% by weight of scrap steel,
and 15% by weight of rejected material such as bead wire.

The cost data are presented in three sections. The first section is for ND process while the second is KEK-BOC process. The third section is for the combined process.

The ND process has three capacity alternatives, namely, the 1, 2 and 3 tonne (throughput) per hour (TPH) units. The throughput capacity of KEK-BOC system depends on the type of mill used. Only one mill, the 2-H mill has the capacity comparable to the smallest of the ND process. However, several of the 2-H mill system may be installed to cater for the higher throughput of the other ND systems. Four possible combinations as discussed in section 7.3 C are

- (I) 1 TPH ND System + 1 x 2-H mill KEK-BOC System
- (II) 2 TPH ND System + 2 x 2-H mill KEK-BOC System
- (III) 3 TPH ND System + 3 x 2-H mill KEK-BOC System
- (IV) 3 TPH ND System + 2 x 2-H mill KEK-BOC System

Cost data for all four combinations are presented in the section G.4.

The cost data is correct for December 1981.

G.2 Cost Data - Newell Dunford Systems

Summary

Designed Throughput Capacity (TPH)	1	2	3
Annual Throughput (tonnes of scrap tyre)	5,640	11,280	16,920
Annual Production of Crumb (tonnes)	3,666	7,332	10,998
Annual Production of Steel Scrap (tonnes)	1,128	2,256	3,384
Annual Production of Rejected Material (tonnes)	846	1,692	2,538
<u>Capital Equipment Costs</u>	£	£	£
Capital price of equipment ex-works	272,600	335,950	371,100
5% UK Delivery Charge	13,630	16,798	18,555
	286,230	352,748	389,655
Contingency of 7.5% of Ex-work price	20,445	25,196	27,833
Erection Electrical Installation & Civil Eng. Works, 35% of Ex-work Price	95,410	117,583	129,885
	402,085	495,527	547,373
<u>Operating Costs (per annum)</u>	£	£	£
<u>Variable Costs</u>			
Power	38,669	41,223	44,168
Spares and Maintenance	5,700	11,400	17,000
Liquid Nitrogen (LIN)	118,440	236,880	355,320
Waste Disposal	8,460	16,920	25,380
Transport of Scrap Tyres	39,480	78,960	118,440
Less Value of Recovered Magnetics	(9,024)	(18,048)	(27,072)
Wages and Salaries	65,803	83,182	83,182
	267,528	450,517	616,418
<u>Fixed Costs</u>			
LIN tank rental	18,000	36,000	54,000
Administration and Other Costs	120,000	120,000	120,000
	138,000	156,000	174,000
Total Operating Costs per annum	405,528	606,517	790,418

Capital Price of Equipment Ex-work

Item \ Designed Throughput	1 TPH	2 TPH	3 TPH
	£	£	£
Shredder	80,000	86,850	98,000
Freezer	50,000	56,000	60,000
Grinder	20,000	47,200	54,000
Screens	24,200	32,100	33,200
Magnetic Separators	25,600	28,000	29,400
Conveyors	22,500	31,000	33,000
Chutes/Steelwork	23,000	24,800	28,500
Dust Collection System	27,300	30,000	35,000
Total (£)	272,600	335,950	371,100

Operating Costs

Power

Designed Throughput	1 TPH	2 TPH	3 TPH
Item	Installed Power (KW)		
1. Feed Conveyor	1.5	1.5	1.5
2. Tyre Shredder	110.0	110.0	110.0
3. Inclined Conveyor	2.5	2.5	2.5
4. Freezing Tunnel	19.0	19.0	19.0
5. Exhaust Fan	7.5	7.5	7.5
6. Hammer Mill	100.0	150.0	150.0
7. Inclined Conveyor	2.5	2.5	2.5
8. Overband Separator	3.2	3.2	3.2
9. Magnetic Separator & Vibrating Feeder	6.0	6.0	6.0
10. Primary Screen	2.2	2.2	2.2
11. Secondary Screen	2.2	2.2	2.2
12. Dust Collection Equipment ⁺	95.0	95.0	95.0
Total Installed Power	351.6	401.6	401.6

⁺ Assumed to be air cleaner of work space.

Designed Throughput	1 TPH	2 TPH	3 TPH
Average Consumption expressed as a % of the total installed power (%)	75	70	75
Average Power Consumption (KW)	263.7	281.1	301.2
Power Cost per annum ⁺ (£)	38,669	41,223	44,169

⁺Unit cost (KW Hr) = 2.6p, 5640 working hours per year

Spares and Maintenance

Plant maintenance is assumed to be carried out by an outside independent company or by maintenance staff from the main company where rubber recycling is part of the operation.

A linear relationship between throughput capacity and spares maintenance is also assumed.

3 TPH plant requires £17,000 per annum

2 TPH plant requires $(£17,000 \div 3) \times 2 = £11,400$ per annum

and 1 TPH plant requires $£17,000 \div 3 = £5,700$ per annum

Cost of Rejects Disposal

The cost of disposal of the rejected material such as textile and bead-wire is assumed to be £10 per tonne.

Designed Throughput	1 TPH	2 TPH	3 TPH
Annual Production of Rejects (tonnes)	846	1,692	2,538
Total Annual Cost of Disposal (£)	8,460	16,920	25,380

Liquid Nitrogen Consumption

The liquid nitrogen (LIN) consumptions are based on the following assumptions;

- (i) Lin usage is independent of the plant size,
- (ii) the LIN usage is 0.42 kg of LIN per kg. of feed,
- and (iii) cost of LIN is £50 per tonne.

The cost of LIN varies according to demand, location of the plant and

the volume consumed. Each individual company would have to negotiate for an agreed price and most likely each price would differ from another. However, £50 per tonne is suggested (121) to be the most probable price for a 3TPH plant.

Designed Throughput	1 TPH	2 TPH	3 TPH
Annual Feed Throughput (tonnes)	5,640	11,280	16,920
Annual LIN Consumption (tonnes)	2,368.8	4,737.6	7,106.4
Annual LIN Consumption (£)	118,440	236,880	355,320

Liquid Nitrogen Tank Rental⁺

The tank rental is in addition to the cost of liquid nitrogen consumed. A tank holds 40 tonnes of LIN. It is assumed that a storage of LIN sufficient for 95 hours of plant running is required. Therefore the number of tanks required by 1, 2 and 3 TPH plants are 1, 2 and 3 tanks respectively.

The annual rental for a tank is £18,000. Therefore the annual liquid nitrogen tank rental is:

⁺ A standard 40-tonne liquid nitrogen storage tank is assumed here. Tanks can be supplied in several sizes. Plants requiring more than one 40-tonne tank may choose to install a large capacity tank. However, tank rentals are subject to individual negotiation, and the rental for several smaller size tanks approximates that for a larger tank of similar total capacity (121).

Design Throughput	1 TPH	2 TPH	3 TPH
Amount of LIN for 95 hours plant running (tonnes)	39.9	79.8	119.7
Required Number of Tank	1	2	3
Annual Tank Rental (£)	18,000	36,000	54,000

Cost of Scrap Tyre

Scrap tyre is the raw material for the cryogenic grinding process. Scrap tyre has zero market value and the only costs involved are the costs of collecting and transporting the tyres to the plant.

The cost of collection and transport is assumed to be £7/tonne.

Therefore the annual costs of scrap tyre for the 3 plants are:

Designed Throughput	1 TPH	2 TPH	3 TPH
Annual costs of Scrap Tyre (£)	39,480	78,960	118,440

Income from the Recovered Magnetics

The steel belts and other ferrous metals which are removed by the magnetic separators are assumed to be saleable as scrap steel at a price of £8 per tonne.

Designed Throughput (TPH)	1	2	3
Annual Income from the Recovered Magnetics (£)	9,024	18,048	27,072

Wages and Salaries

The manning of the plant is based on 3 8-hour shifts per day and 5 days per week. The level of manning depends on the throughout capacity of the plant. For a 3 TPH and 2 TPH plant, each shift consists of 1 senior plant operator, 1 plant operator and 2 labourers. For a 1 TPH plant, only 1 senior plant operator, 1 plant operator and 1 labourer are assumed.

The salary scales have been obtained from PA491, Business Monitor, HMSO, (144).

<u>3 TPH Plant and 2 TPH Plant</u>	<u>Salary per annum (£)</u>
6 labourers @ £5,793	34,758
3 plant operators @ £5,793	17,379
3 senior plant operators @ £7,015	21,045
Services of maintenance crew	10,000
	<hr/>
Total Salaries per annum	£83,182
	<hr/> <hr/>

<u>1 TPH Plant</u>	<u>Salary per annum (£)</u>
3 labourers @ £5,793	17,379
3 plant operators @ £5,793	17,379
3 senior plant operators @ £7,015	21,045
Services of maintenance crew	10,000
	<hr/>
Total Salaries per annum	£ 65,803
	<hr/>

Other Costs : Fixed

The administrative and technical support is given by a team of a managing director/general manager, a plant/production manager, 2 technicians, 2 sales representatives, 2 secretaries and 2 accounts clerks. The other costs consist of office expenses, rent and rates for all buildings and warehouse expenses. This item of cost is assumed to be the same for all 3 capacity plants.

	<u>Salary per annum (£)</u>
1 Managing Director/General Manager	10,000
1 Plant/Production Manager	8,000
2 Technicians @ £4,000	8,000
2 Sales Representatives @ £5,000	10,000
2 Accounts Clerks @ £6,000	
	+ £4,000
	10,000
2 Secretaries	7,000
	<hr/>
	53,000
Others ⁺	67,000
	<hr/>
	£120,000
	<hr/>

⁺Includes rent and rates for factory buildings, offices, warehouse etc., internal transport, warehouse staff and expenses etc. LIN tank rental not included.

Summary

No. of 2-H Mill	1	2	3
Maximum Throughput (tonnes)	0.8	1.6	2.4
Max. Throughput (tonnes per annum)	4,512	9,012	13,536
Total Capital Equipment Cost	80,000	140,000	200,000
<u>Operating Costs</u>			
<u>Variable Costs</u> ⁺			
Power	6,340	12,680	19,020
Spares and Maintenance	1,000	2,000	3,000
LIN Consumption	180,480	360,960	541,440
Wages and Salaries	5,793	5,793	5,793
	193,613	381,433	569,253
<u>Fixed Costs</u>			
LIN tank rental	36,000	54,000	36,000
Total Operating Cost per Annum	229,613	435,433	605,253

+ assume there is a linear relationship between total variable costs and output.

Capital Equipment Costs

Detail breakdown of the costs for the capital equipment for the KEK-BOC system based on a 2-H mill are not available. A gross sum of £80,000 is quoted for a fully installed system based on a 2-H mill which has the following components :

ITEM

- 1 The 2-H mill; including stainless steel casing, horizontal mounting and 37 KW motor.
- 2 The Pinned Disk : a pair, stainless steel, 19" diameter.
- 3 Suction Feed System : mild steel.
- 4 Filter : reverse-jet filter.
- 5 Control Panel and Control Systems.
- 6 Ancillary : stands, rotary valves etc.
- 7 Centrifugal Sifter.

Some of the components, such as the filter, the control panel and

control system, the sifter, may be shared by another mill or mills. It is assumed that the additional cost of installing an additional 2-H mill is £60,000. Therefore, the capital equipment costs of 1, 2 and 3 mills may be summarised as :

No. of 2-H Mill	1	2	3
Capital Equipment Cost (fully installed) (£)	80,000	140,000	200,000

Operating Costs

Power

The estimated installed power is summarised below :

EQUIPMENT	ESTIMATED INSTALLED POWER (KW)
Screw Feed	1.5
Conveyor	1.5
Mill	37
Miscellaneous	20
Total Installed Power for a 2-H Mill System	60

The average power consumption of the system is assumed to be 75% of the total installed power.

$$75\% \text{ of installed power} = 60\text{KW} \times 0.75 = 45\text{KW}$$

No. of 2-H Mill	1	2	3
Power Consumption per annum ⁺ (KWH)	243,800	487,600	731,400
Power Consumption p.a. (£)	6,340	12,680	19,020

+ unit cost (KWH) = 2.6p ; 5640 working hours per year.

Spares and Maintenance

The most likely component of the system which may require frequent maintenance is pins of the disk mill. As individual pin can be replaced, the cost of the spare would be small. Other areas which may require periodical service and maintenance are the screen of the sifter, the filter system and small parts such as bearings of the screw feed system. The estimated cost for the spares and maintenance for a system based on

a 2-H mill is £1,000 per annum.

No. of 2-H Mill	1	2	3
Spares and Maintenance p.a. (£)	1,000	2,000	3,000

Liquid Nitrogen Consumption

The LIN usage for the KEK - BOC system is 0.8 kg of LIN per kg of rubber feed. Based on a 5640 working hours / year, the LIN consumption may be calculated as :

No. of 2-H Mill	1	2	3
Maximum Throughput (TPH)	0.8	1.6	2.4
Rubber Processed p.a. (tonnes)	4,512	9,024	13,536
LIN consumption p.a. (tonnes)	3,609.6	7,219.2	10,828.8
LIN consumption p.a. (£) ⁺	180,480	360,960	541,440

+ cost of LIN = £50 per tonne.

Liquid Nitrogen Tank Rental

As discussed in Section G.2, tank rental is in addition to the cost of LIN consumed. Assuming 95 hours of LIN stock is required, the tank rental costs may be calculated as :

No. of 2-H Mill	1	2	3
Amount of LIN for 95 Hours of Plant Running (tonnes)	60.8	121.6	182.4
No. of Tank Required	2	3	5

Five LIN storage tanks are required to support 3 2-H mills. If Plant Combination III (see Chapter 7) is considered, another 3 tanks are needed to sustain the primary grinding system making a total of 8 tanks which is unrealistic. Therefore it is assumed that a maximum of 5 tanks and increase the frequency of LIN delivery. Another alternative is to increase the tank size.

Wages and Salaries

Given that the KEK - BOC system has a high degree of automation, and that the system is to be joined to the ND system, an additional unskilled labour is assumed to be sufficient for the 1, 2 or 3 mill

systems. Salary for an unskilled labourer in the rubber industry is £5,793 per annum (144).

G.4 SUMMARY OF COST DATA FOR COMBINED ND, KEK-BOC PROCESS

Combination	I			II			III			IV		
ND	1 TPH			2 TPH			3 TPH			3 TPH		
Max. Product Output pa (tonne)	3,660			7,332			10,998			10,998		
KEK-BOC	1 x 2-H Mill			2 x 2-H Mills			3 x 2-H Mills			2 x 2-H Mills		
Max. Product Output pa (tonne)	4,512			9,024			13,536			9,024		
Max. Production Output for the Combination (tonne)	3,666			7,332			10,998			9,024		
Capital Costs												
ND	402,085			495,527			547,373			547,373		
KEK-BOC	80,000			140,000			200,000			140,000		
	482,085			635,527			747,373			687,373		
Operating Costs												
Variable Costs :												
Power	£	%	%	£	%	%	£	%	%	£	%	%
Spares and Maintenance	45,009	9.76	7.09	53,903	6.48	5.17	63,188	5.33	4.53	56,848	5.70	4.70
LIN Consumption	6,700	1.45	1.05	13,400	1.61	1.29	20,000	1.69	1.43	19,000	1.90	1.50
Waste Disposal	298,920	64.82	47.06	597,840	71.86	57.38	896,760	75.63	64.25	716,280	71.78	59.30
Transport of Scrap Tyres	8,460	1.83	1.33	16,920	2.03	1.62	25,380	2.14	1.82	25,380	2.54	2.10
less Value of Recovered Magnetics	39,480	8.56	6.22	78,960	9.49	7.58	118,440	9.99	8.49	118,440	11.87	9.81
Wages and Salaries	(9,024)	-1.96	-1.42	(18,048)	-2.17	-1.73	(27,072)	-2.28	-1.94	(27,072)	-2.71	-2.24
	71,596	15.52	11.27	88,975	10.69	8.54	88,975	7.50	6.38	88,975	8.92	7.30
Fixed Costs :												
LIN tank rental	461,141	100%	72.60	831,950	100%	79.85	1,185,671	100%	84.95	997,851	100%	82.61
Administration and Other Costs	54,000		8.50	90,000		8.64	90,000		6.45	90,000		7.45
	120,000		18.89	120,000		11.52	120,000		8.60	120,000		9.94
Total Operating Costs	174,000		27.40	210,000		20.15	210,000		15.05	210,000		17.39
	635,141		100%	1,041,950		100%	1,395,671		100%	1,207,851		100%
Variable Cost per tonne of Output	£125.79			£113.47			£107.81			£110.58		
Total Operating Cost per tonne of Output	£173.25			£142.11			£126.90			£133.85		

INVESTMENT APPRAISAL TECHNIQUES

The investment appraisal techniques used in the economic analysis of Chapter 5 are based on two Discounted Cash Flow techniques; Net Present Value (NPV) and Internal Rate of Return (IRR). The NPV and IRR are two of the major and most common Discounted Cash Flow (DCF) measures of the economic value of a proposed investment. Both techniques have the same basis; they are based on projected cash flows, on the time value of money, and on the whole life of the proposed investment. Both techniques are independent of the arbitrarily chosen methods of estimating depreciation, as the techniques inherently make provision for the recovery of the capital expenditure.

H.1 Net Present Value (NPV)

The NPV is equal to the difference between the sum of the present values of the projected cash flows of a project and the present value of the investment in capital assets and working capital. Since money can be invested to earn interest, a sum of money received today has a greater present value than if received on a future time. Therefore, a sum of money receivable in a future time will have a lower present value than if the same amount is received today. Present values of future cash flows are derived by the method known as "discounting", which is the reverse of compound interest calculations. Given a prevailing rate of interest of 10% per annum, £500 receivable in two years time would be worth today:

$$500 = A (1 + 0.10)^2$$

A = present value of the £500 receivable in two years

$$A = 500 \times \frac{1}{(1.1)^2}$$

$$= 500 \times 0.8264$$

$$= 413.22$$

0.8264 is known as a discount factor.

Future cash flows of a project are reduced to present values using

such discount factors. Generally, the NPV of a project with capital expenditure K, and project life N would be:

$$NPV = -K + a_1 \times \frac{1}{(1+r)^1} + a_2 \times \frac{1}{(1+r)^2} + \dots + a_N \times \frac{1}{(1+r)^N} \quad (H.1)$$

where a_i 's are the net cash flows in the appropriate year of the project, and r is the discount rate.

The equation for NPV may be simplified to:

$$NPV = -K + \sum_{i=1}^N a_i \times \frac{1}{(1+r)^i} \quad (H.2)$$

For a project which generates even cash flows over its life, this equation may be simplified further to:

$$NPV = -K + a \sum_{i=1}^N \frac{1}{(1+r)^i} \quad (H.3)$$

where $\sum_{i=1}^N \frac{1}{(1+r)^i}$ is known as the present value annuity factor, which may be resolved into $\left[\frac{1 - (1+r)^{-N}}{r} \right]$.

K, the capital expenditure consists of the initial outlay of capital equipment and assets, and the working capital.

r , the discount rate, the determination of which is discussed in Chapter 7.

a_i , the net cash flow after tax for the i^{th} year. a_i 's should not include any depreciation charges although capital allowance is deducted from the net operating cash flows for calculating the amount of taxes incurred. Taxes (assuming a one year lag in tax payment) are calculated from the taxable profit where

$$\text{Taxable Profit} = \underbrace{(\text{Cash Income} - \text{Total Operating Costs})}_{\text{Net Operating Cash Flow}} - \text{Capital Allowance}$$

and

$$\text{Tax Payable in Year } (i + 1) = \left(\frac{\text{Taxable Profit in Year } i}{\text{Year } i} \right) \times \text{Tax Rate}$$

H.2 Internal Rate of Return (IRR)

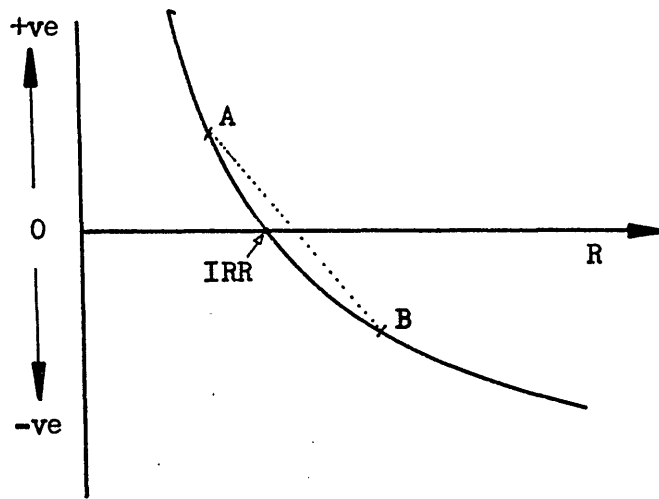
The IRR may be defined as the discount rate that makes the present value of the future net cash flows equal to the present value of the cost of the project. Alternatively, IRR may be considered as the maximum rate of interest that could be paid for the capital employed over the life of an investment without loss on the project. Therefore, when the discount rate is equal to IRR, a zero NPV is obtained, i.e.

$$\text{NPV} = -K + \sum_{i=1}^N a_i \times \frac{1}{(1+R)^i} = 0$$

$$\text{or} \quad K = \sum_{i=1}^N a_i \times \frac{1}{(1+R)^i} \quad (\text{H.4})$$

where R is the IRR of the project.

The IRR is obtained by solving the equation H.4. Equation H.4 can be reduced to a polynomial equation in R(143). The longer the project life, the higher the degree of the polynomial equation. Solving such an equation involves trial and error. The approach is to pick an estimated discount rate and calculate the NPV. If NPV is positive, a high rate is tried in the next calculation; if it is negative, a lower rate is tried. The procedure continues until a rate is found where NPV is equal to zero. However, in practice it would be too time consuming to find a rate which would achieve zero NPV, and given that there is a certain degree of uncertainty in the cash flow forecasts, the additional accuracy in IRR may not be worth the effort. An interpolation method is usually employed.



A good estimate of IRR is obtained by interpolating between the two rates which give a small positive (A) and small negative (B) NPV's (see diagram). Such an iterative method has been used in the computer program (in section H.4) to solve for the IRR of the projects under consideration.

It is possible for a project to have multiple IRR. This usually occurs when there is more than one change in sign in cash flows from a positive to a negative (see for example reference 143 for more detail discussion on multiple IRR). The problem of multiple IRR does not exist in the projects under consideration since there is only one change in sign in the cash flows.

H.3 Breakeven Analysis

Conventionally, short term breakeven analysis is performed to allow a decision to be made between operating and shut-down. Hence, short term B/E price is an out-of-pocket cash B/E price which includes only the variable costs of production) and the cash fixed costs in its calculation.

Short Term B/E Price = Variable Cost per Unit + Fixed Cost per Unit

Short Term B/E Volume =
$$\frac{\text{Fixed Cost}}{\text{Marginal Contribution}}$$

The short term B/E analysis does not account for the recovery of capital invested, nor the interest charges or the effect of taxation. This short term B/E analysis can be modified (179) to make it applicable to the analysis of investment projects by allowing for the factors mentioned above. Hence, in effect, these long term breakeven

(L.T. B/E) conditions are satisfied when the project yields a zero NPV. IRR is, therefore, the L.T. B/E discount rate. Similarly, the required minimum or maximum values (depending on the nature of the cost item) to satisfy the L.T. B/E condition can be calculated. A sensitivity analysis can be performed using these L.T. B/E values whereby the most critical variable can be identified.

The equations for the L.T. B/E values are developed from the NPV equation (H.1) with slight modifications. With the cryogenic grinding process, the net operating cash flow is derived from

$$(P - VC) \times \frac{CU}{100} \times C - FC$$

where P is the output price per tonne; VC is the total variable costs per tonne; CU is the percentage of capacity utilisation; C is the maximum technical design capacity and FC is the fixed cost per annum.

First, consider the no tax case, the project with capital investment K, working capital WC and discount rate of R will yield a NPV of

$$NPV = -K - WC + \left[(P - VC) \times \frac{CU}{100} \times C - FC \right] \times A_{N/R} + WC \times V_R^N \quad (H.5)$$

where $A_{N/R}$ is the annuity discount factor for R% and N years, and V_R^N is the present value of £1 discount factor for R% and year N. The term $WC \times V_R^N$ is the working capital recovery at end of the project, in this case year N

For breakeven point, NPV = 0. Therefore,

$$-K - WC + \left[(P - VC) \times \frac{CU}{100} \times C - FC \right] \times A_{N/R} + WC \times V_R^N = 0$$

$$\text{Rearrange, } P = \left[\frac{\left(\frac{K + WC(1 - V_R^N)}{A_{N/R}} \right) + FC}{\frac{CU}{100} \times C} \right] + VC \quad (H.6)$$

By manipulating equation H.6 and substituting working capital, WC, by

$$WC = \frac{118440}{6} \times \frac{CU}{100} + \frac{VC}{6} \times \frac{CU}{100} \times C + \frac{FC}{6} \quad (H.7)$$

where the first term is two months cost of material (scrap tyres) supply, and the last two terms represent two months worth of finished product, expressions for K, FC, CU, VC and N can be obtained. These expressions are listed below :

$$K = \left((P - VC) \times \frac{CU}{100} \times C - FC \right) \times A_{N/R} - WC \times (1 - V_R^N)$$

$$K + FC \times (A_{N/R} + (1 - V_R^N)/6)$$

$$CU = \frac{(P - VC) \times \frac{C}{100} \times A_{N/R} - \left(\frac{118440}{600} + \frac{C}{600} \times VC \right) (1 - V_R^N)}{}$$

$$FC = \frac{CU \times \left[(P - VC) \times \frac{CU}{100} \times A_{N/R} - \left(\frac{118440}{600} + \frac{C}{600} \times VC \right) (1 - V_R^N) \right] - K}{(A_{N/R} + (1 - V_R^N) / 6)}$$

$$VC = \frac{(P \times \frac{CU}{100} \times C - FC) \times A_{N/R} - \left(\frac{118440}{6} \times \frac{CU}{100} + \frac{FC}{6} \right) (1 - V_R^N) - K}{((1 - V_R^N) / 6 + A_{N/R}) \times \frac{CU}{100} \times C}$$

and

$$N = \frac{\log \left[\left(1 - \frac{K \times R}{(Y)} \right)^{-1} \right]}{\log (1 + R)}$$

where

$$(Y) = (P - VC) \times \frac{CU}{100} \times C - FC - WC \times R$$

R at B/E point is the IRR and can be obtained by the technique of trial and error, and interpolation.

With the introduction of corporation tax, T, there are three additional factors to be considered. They are

- a) tax payables on the net cash flows ;
- b) time lag of one year in tax payment ; and
- c) capital allowance of full capital costs.

The company undertaking the project is assumed to have sufficient taxable income to take the benefit of the available tax allowance, and that full capital allowance is claimed in year two.

Ignoring the effect of time lag for a moment, the introduction of tax will require two extra terms. One for the tax payables :

$$- T \times \left[(P - VC) \times \frac{CU}{100} \times C - FC \right] \times A_{N/R}$$

and the capital allowance term :

$$+ K \times T \times V_R^2 .$$

The time lag in tax payment can be accounted for by first adding the amount equivalent to the tax payment to the cash flows in year one, and then subtracting a tax bill in year (N+1), i.e.

$$+ T \times \left[(P - VC) \times \frac{CU}{100} \times C - FC \right] \times V_R^1 - T \times \left[(P - VC) \times \frac{CU}{100} \times C - FC \right] \times V_R^{N+1}$$

or

$$T \times (V_R^1 - V_R^{N+1}) \times ((P - VC) \times \frac{CU}{100} \times C - FC)$$

Incorporating these terms into equation H.5, the equation for NPV becomes

$$\begin{aligned} NPV = & - K \times (1 - T \times V_R^2) - WC \times (1 - V_R^N) + \\ & ((P - VC) \times \frac{CU}{100} \times C - FC) \times ((1-T) \times A_{N/R} + T \times (V_R^1 - V_R^{N+1})) \end{aligned}$$

For B/E point, NPV = 0. Therefore,

$$\begin{aligned}
& ((P - VC) \times \frac{CU}{100} \times C - FC) ((1-T) \times A_{N/R} + T \times (V_R^1 - V_R^{N+1})) \\
& = K \times (1 - T \times V_R^2) + WC \times (1 - V_R^N)
\end{aligned}$$

Rearrange,

$$P = VC + \left[\frac{\left[\frac{K \times (1 - T \times V_R^2) + WC \times (1 - V_R^N)}{(1-T) \times A_{N/R} + T \times (V_R^1 - V_R^{N+1})} + FC \right]}{\frac{CU}{100} \times C} \right] \quad (H.8)$$

Again, by manipulating equation H.8 and substituting the WC with equation H.7, expressions for K, FC, CU and VC can be obtained. In order to avoid complicated looking expressions and having to write some terms repeatedly, some abbreviations are used :

let

$$Y1 = (1-T) \times A_{N/R} + T \times (V_R^1 - V_R^{N+1}) ;$$

$$Y2 = 1 - T \times V_R^2 ;$$

$$\text{and} \quad Y3 = 1 - V_R^N .$$

All these factors i.e. Y1, Y2 and Y3 are independent of P, VC, CU, C, FC and K. The expressions are :

$$P = \left[\frac{\frac{K \times Y2 + WC \times Y3}{Y1} + FC}{\frac{CU}{100} \times C} \right] + VC$$

$$K = \frac{((P - VC) \times \frac{CU}{100} \times C - FC) \times Y1 - WC \times Y3}{Y2}$$

$$FC = \frac{(P - VC) \times \frac{CU}{100} \times C \times Y1 - K \times Y2 - \left(\frac{118440}{6}\right) \times \frac{CU}{100} + \frac{CU}{600} \times C \times VC \times Y3}{\frac{1}{6} \times Y3 + Y1}$$

$$CU = \frac{K \times Y2 + \left(\frac{1}{6} \times Y3 + Y1\right) \times FC}{(P - VC) \times \frac{CU}{100} \times Y1 - \frac{118440}{600} \times Y3 - \frac{C}{600} \times VC \times Y3}$$

$$VC = \frac{P \times \frac{CU}{100} \times C \times Y1 - \frac{118440}{6} \times \frac{CU}{100} \times Y3 - K \times Y2 - FC \times \left(\frac{1}{6} \times Y3 + Y1\right)}{\frac{CU}{100} \times C \times \left(\frac{1}{6} \times Y3 + Y1\right)}$$

The expressions for R and N, which are more complex and involving a large number of terms, have not been obtained. The B/E R and N for the tax case can be obtained by the technique of trial & error and interpolation.

H.4 Computer Program for Investment Appraisal

A computer program is developed to perform the laborious task of applying the investment appraisal techniques described in Sections H.1, H.2 and H.3 (except the long term B/E values).

The flow diagram for the computer program is shown in Figure H.1. The program has two major branches, one branch for NPV / IRR calculations, and the other for sensitivity analysis.

(a) NPV and IRR Calculations

Equation H.2 is used in the NPV calculations. There are three methods of cash flows input after entering the initial cost data into the program :

- i) cash flows calculated by the computer ;
- ii) even cash flows enter by the user ; and
- iii) uneven cash flows enter by the user.

Working capital is taken as two months raw material supplies and two months inventory of finished goods. Working capital is added to the beginning of the project life and is recovered at the end of it. Working

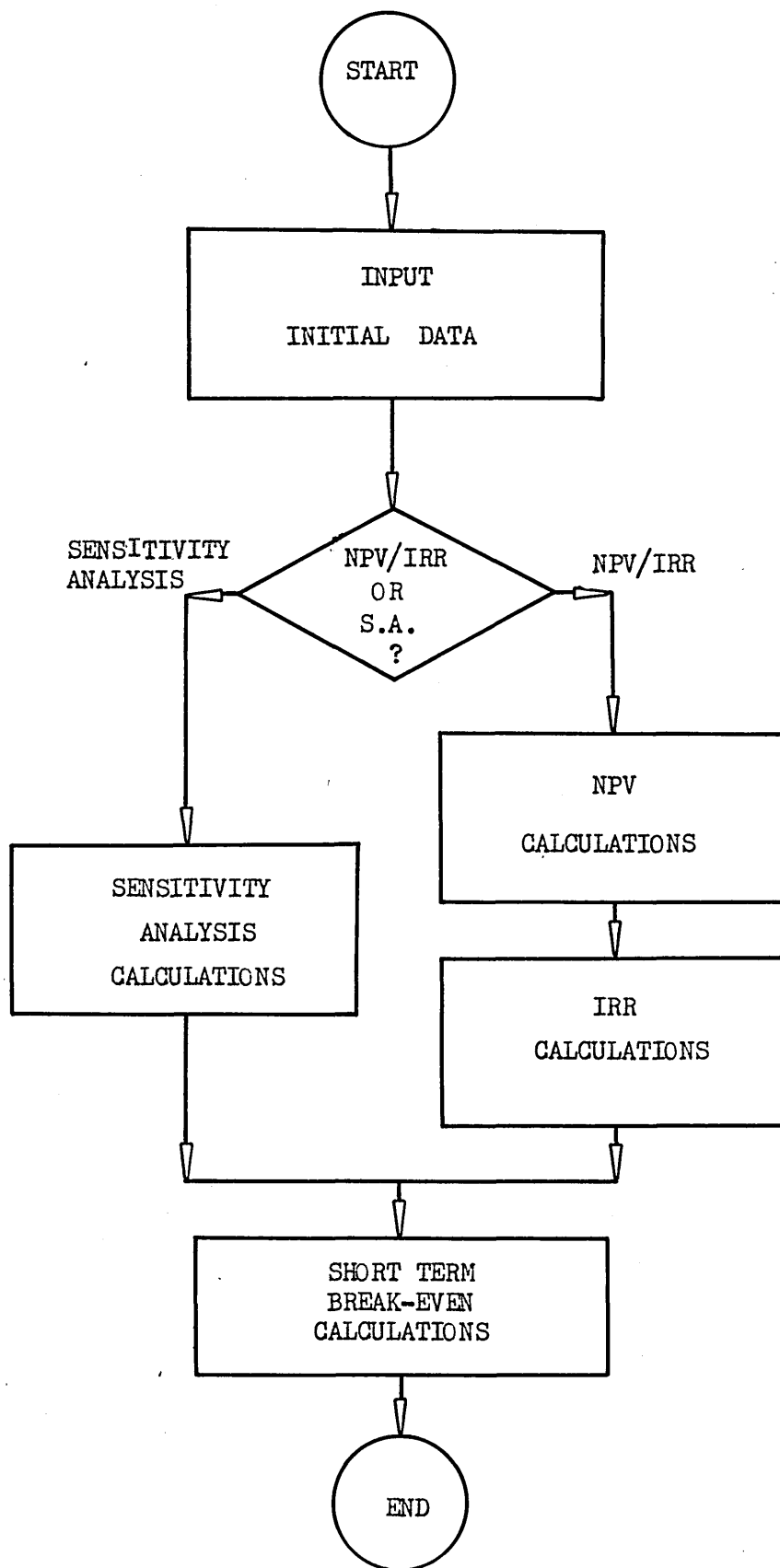


FIGURE H.1 Flow Diagram for the Computer Program for Investment Appraisal.

capital is accounted automatically.

Capital allowance is only used for taxation purposes and is used to calculate taxable profit where

Taxable Profit = Cash Income - Total Operating Costs - Capital Allowance

The capital allowance is claimed in the earliest possible period.

The tax rate may be chosen. If a zero rate is chosen, the calculation will proceed as if taxation is excluded. Only taxable profit is taxed and taxes are payable after one year of the taxable profit.

NPV may be calculated at one discount rate, or a range of discount rates may be chosen.

IRR is defined as the discount rate when $NPV = 0$. Again equation H.2 is used to calculate NPV. The absolute accuracy in obtaining $NPV = 0$ at IRR is traded off with processing time by redefining IRR as the discount rate when $NPV = \pm 1\%$ of capital costs. The range of IRR that can be handled is $\pm 50\%$, IRR beyond this range will be indicated.

(b) Sensitivity Analysis⁺

The basis of the sensitivity analysis is the NPV of the project. The factors that can be studied are :

- i) price of the output ;
- ii) capital costs ;
- iii) fixed costs ;
- iv) variable costs ;
- v) power consumption ;
- vi) liquid nitrogen consumption ; and
- vii) labour costs .

A range of changes (from the initial input data) may be chosen. However, only one variable is changed at any one computation while others are held constant at original values.

The NPV's are calculated by equation H.2 with a discount rate, which can be altered. Working capital, capital allowance and taxation are treated as in NPV - IRR calculations.

⁺Note: This is the traditional sensitivity analysis (with a fixed % change in one variable) and is different from the sensitivity analysis using the long term B/E values in Chapter Seven.

(c) Short Term Breakeven Analysis

The short term B/E price and volume are calculated using :

Short Term B/E Price = Variable Cost per unit + Fixed Cost per unit

$$\text{Short Term B/E Volume} = \frac{\text{Fixed Costs}}{\text{Marginal Contribution}}$$

The computer program is not capable of calculating the long term B/E values as described in Section H.3.

(d) Computer Program Listing

A listing of the computer program is included at the end of this Appendix.

(e) Limitations of the Computer Program

This computer program is tailored for the ND, KEK-BOC process and therefore cannot be used for other process without modifications. Such modifications would be simple for other cryogenic grinding processes.

The other limitations of the program are :

i) the maximum project life is 25 years. This limitation may be remedied by redimensioning the arrays used if the computer has sufficiently large memory capacity.

ii) the NPV calculation breaks down with continuous negative cash flows, and will give an increasingly large negative NPV with increasing discount rate. Negative cash flows will be indicated if used to calculate IRR.

iii) the IRR calculation cannot handle multiple IRR problems due to the use of the simple iterative method for its determination.

iv) in the sensitivity analysis, it is not possible to change the base values without re-entering the initial data.

v) the sensitivity analysis only permits one variable to flex at a time while holding others constant.

COMPUTER PROGRAM LISTING

```
10 HOME : CLEAR
20 DIM C(25,25),D(25,25),T(25,25),X(25,25),R(100),CU(25),V(25),P(25),VC(25),Y(25),M(25)
30 DIM DP(25,25),K(25),LN(25),E(25),LB(25),FC(25),FG(25),WC(25)
40 Y$ = "Y":N$ = "N": HOME
41 PRINT TAB( 10)"THIS IS COMBINED AA": PRINT
42 PRINT TAB( 10)"IT PERFORMS BOTH :-": PRINT
43 PRINT TAB( 15)"NPV & IRR CALCULATIONS": PRINT
44 PRINT TAB( 13)"& SENSITIVITY ANALYSIS.": PRINT : PRINT
45 PRINT "THE NPV & IRR IS CALCULATED BY": PRINT "'GRAND MESS'": PRINT
46 PRINT "THE SENSITIVITY ANALYSIS IS EVALUATED BY": PRINT "'SENSEAN'": PRINT
47 PRINT "-:YOU MAY SWITCH FROM ONE TO THE OTHER:-
50 PRINT "DO YOU WISH TO PERFORM SENSITIVITY ANALYSIS OR NPV/IRR CALCULATION ?"
60 PRINT
70 PRINT "TYPE SA FOR SENSITIVITY ANALYSIS,": PRINT TAB( 6)"NPV FOR NPV/IRR CALCULATIO
   .": INPUT QA$
80 S$ = "SA":R$ = "NPV"
90 IF QA$ < > S$ THEN IF QA$ < > R$ GOTO 70
100 HOME :MI = 0:CE = 0:CU(1) = 0
110 INPUT "ENTER THE PROJECT LIFE IN YEARS ";N: PRINT
120 INPUT "ENTER THE TOTAL INVESTMENT ";K1: PRINT
130 INPUT "ENTER THE OUTPUT PRICE PER TONNE ";P(1): PRINT
140 INPUT "ENTER THE DESIGN CAPACITY IN T.P.H. ";CE: PRINT
142 IF CE > 3 THEN PRINT "DESIGN CAPACITY MUST BE 1,2 OR 3.": PRINT : GOTO 140
144 IF CE = 1 THEN PRINT "1 2-H MILL IS USED.": PRINT : GOTO 158
146 IF CE = 2 THEN PRINT "2 2-H MILLS ARE USED.": PRINT : GOTO 158
148 IF CE = 3 THEN PRINT "HOW MANY MILLS ARE USED ? ENTER 2 OR 3 ": INPUT MI: PRINT
150 IF MI < > 2 THEN IF MI < > 3 GOTO 148
158 FO = CE * 5640 * .65
159 IF MI = 2 THEN FO = FO * .8
160 INPUT "ENTER CAPACITY UTILITY IN % ";CU(1): PRINT
165 IF CU(1) > 100 THEN PRINT "** FIGURE IN % BETWEEN 0 - 100 ! **": PRINT : GOTO 160
170 INPUT "ENTER TOTAL FIXED COSTS P.A. ";FC: PRINT
180 INPUT "ENTER VARIABLE COST PER TONNE ";VC(1): PRINT
182 PRINT "DO YOU WISH TO CHANGE SAME DATA ?": PRINT : PRINT "YOU'D HAVE TO RE-ENTER ALL
   THE DATA!": PRINT
184 GOSUB 2930: INPUT QD$: PRINT
185 IF QD$ = Y$ GOTO 100
190 IF QA$ = S$ GOTO 1790
200 HOME : PRINT : PRINT : PRINT : PRINT : PRINT : PRINT
210 PRINT "      THIS IS GRAND MESS OK": PRINT
220 PRINT "      WHICH CALCULATES": PRINT
230 PRINT "      NPV & IRR": PRINT
240 PRINT : PRINT : PRINT
250 INPUT "PRESS <RETURN> KEY TO START ";QW$
260 HOME : GOSUB 2960
270 INPUT "PRESS <RETURN> KEY TO START ";QW$
272 HOME : GOSUB 4600: REM CALC C'S
273 PRINT
274 PRINT "DO YOU WISH TO USE THESE CASH FLOWS ?": GOSUB 1760: INPUT QE: PRINT
276 IF QE = 0 GOTO 320
280 HOME : PRINT "DO YOU HAVE EVEN OR UNEVEN CASH FLOWS ?": PRINT
290 PRINT "      TYPE": PRINT "      0 FOR EVEN CASH FLOW": PRINT "      1 FOR UNE
   EN CASH FLOWS": INPUT Q1: PRINT
300 IF Q1 = 0 THEN GOSUB 650
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310 IF Q1 > 0 THEN GOSUB 710
320 HOME : GOSUB 1250
330 GOSUB 1430
340 PRINT "THE TOTAL WORKING CAPITAL EXCL. LAND IS "WC
350 K = K1 + WC
360 GOSUB 1280
370 GOSUB 1310
380 PRINT "DO YOU WISH TO INCLUDE TAX ?": PRINT
390 GOSUB 1760: INPUT QB: PRINT
400 IF QB = 0 THEN GOSUB 1490
410 IF QB = 1 THEN GOSUB 1590
420 HOME
430 PRINT "DO YOU WISH TO EXAMINE THE EFFECT OF      DISCOUNT RATES ON NPV'S ?": PRINT
440 GOSUB 1760: INPUT Q2: PRINT
450 IF Q2 = 0 THEN GOSUB 810
460 IF Q2 > 0 THEN GOSUB 760
470 PRINT : PRINT : PRINT "DO YOU WISH TO DETERMINE THE IRR ?": PRINT
480 GOSUB 1760: INPUT Q7: HOME
490 IF Q7 = 0 THEN GOSUB 1030
500 IF Q7 > 0 GOTO 510
510 PRINT : PRINT : IF QB = 0 THEN N = N - 1
520 PRINT "DO YOU WISH TO PERFORM MORE NPV/IRR ": PRINT "CALCULATIONS ? ": PRINT
530 GOSUB 1760: INPUT Q5: PRINT
540 HOME
550 IF Q5 > 0 GOTO 600
560 IF Q5 = 0 GOTO 380
600 PRINT "DO YOU WISH TO PERFORM SENSITIVITY": PRINT "ANALYSIS ?"
610 GOSUB 1760: INPUT Q8: PRINT
620 IF Q8 = 0 GOTO 1790
630 IF Q8 = 1 GOTO 2540
640 IF Q8 < > 0 THEN IF Q8 < > 1 GOTO 600
650 REM == TO ENTER EVEN CASH FLOW==
660 INPUT "ENTER THE EVEN CASH FLOW ";C
670 FOR I = 1 TO N
680 C(0,I) = C
690 NEXT I
700 RETURN
710 REM ==TO ENTER UNEVEN CASH FLOWS==
720 FOR J = 1 TO N
730 PRINT "CASH FLOW IN YEAR "J" IS ": INPUT C(0,J): PRINT
740 NEXT J
750 RETURN
760 REM ==SINGLE R NPV==
770 HOME
780 INPUT "ENTER THE DISCOUNT RATE IN % ";R: PRINT : PRINT
790 GOSUB 1670
800 RETURN
810 REM ==EFFECT OF R'S ON NPV==
820 HOME
830 PRINT "DO YOU WISH TO CHOOSE THE RANGE OF      DISCOUNT RATES ?": PRINT
840 PRINT "THE RANGE WILL BE SET AT -20% TO +50% IF NOT CHOSEN BY YOU ": PRINT
850 GOSUB 1760: INPUT Q3: PRINT
860 IF Q3 = 0 GOTO 880

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870 E1 = - 20:E2 = 50: GOTO 910
880 INPUT "ENTER LOWER R LIMIT EG.-15% AS -15 ";E1: PRINT
890 INPUT "ENTER UPPER R LIMIT EG.+25% AS 25 ";E2: PRINT
900 HOME
910 PRINT "THE RANGE OF R IS "E1"% TO "E2"%: PRINT
920 PRINT "DO YOU WISH TO CHOOSE THE INCREMENT STEP ?": PRINT
930 PRINT "THE INCREMENT STEP WILL BE SET AT 5% IF NOT CHOSEN BY YOU ": PRINT
940 GOSUB 1760: INPUT Q4: PRINT
950 IF Q4 = 0 GOTO 970
960 W1 = 5: GOTO 980
970 INPUT "ENTER THE INCREMENT STEP ";W1: PRINT
980 HOME
990 FOR R = E1 TO E2 STEP W1
1000 GOSUB 1670
1010 NEXT R
1020 RETURN
1030 REM ==IRR DETERMINATION==
1035 IF Q2 = 0 OR Q1 = 0 THEN IF C(0,1) < 0 GOTO 1234
1040 R = 0
1050 GOSUB 1670
1060 AA = V * 100 / K1
1070 IF R > 50 GOTO 1200
1080 IF R < - 50 GOTO 1220
1090 IF ABS (AA) < = 10 THEN 1120
1100 IF SGN (V) = 1 THEN R = R + 2: GOTO 1050
1110 IF SGN (V) = - 1 THEN R = R - 2: GOTO 1050
1120 IF ABS (AA) < = 1 THEN 1180
1130 S = S + 1:R(S) = R: IF S < 3 GOTO 1160
1140 IF R(S - 2) = R(S) THEN Z2 = Z2 + 1
1150 IF Z2 = > 5 THEN GOSUB 1630: GOTO 1180
1160 IF SGN (V) = 1 THEN R = R + .5: GOTO 1050
1170 IF SGN (V) = - 1 THEN R = R - .5: GOTO 1050
1180 PRINT : PRINT "#####": PRINT : PRINT "THE IRR IS DETERMINE
AS "R"%."
1190 PRINT : PRINT "#####": GOTO 1240
1200 PRINT : PRINT "+++++": PRINT : PRINT "THE IRR IS GREATER T
AN +50%."
1210 PRINT : PRINT "+++++": GOTO 1240
1220 PRINT : PRINT "-----": PRINT : PRINT "THE IRR IS LESS THAN
-50%. "
1230 PRINT : PRINT "-----": GOTO 1240
1234 PRINT : PRINT "?????????????????????????????????????": PRINT "NEG. CASH FLOWS : IRR MEAN
INGLESS": PRINT "?????????????????????????????????????": PRINT
1240 Z2 = 0: RETURN
1250 PRINT "WORKING CAPITAL WILL BE AUTOMATICALLY": PRINT "ADDED TO THE CAPITAL INVESTME
T AND": PRINT "RECOVERED AT THE END OF THE PROJEST.": PRINT : PRINT "WORKING CAPITAL
IS TAKEN AS": PRINT : PRINT TAB( 10)"2 MONTHS RAW MATERIAL SUPPLY": PRINT TAB( 10)'
2 MONTHS FINISHED GOODS STOCK"
1260 PRINT : PRINT
1270 RETURN
1280 PRINT "DEPRECIATION OF CAPITAL IS PERFORMED": PRINT "AUTOMATICALLY FOR TAXATION PUR
POSES.": PRINT : PRINT "MAXIMUM DEPRECIATION IS DEDUCTED FROM": PRINT "THE EARLIEST P
SSIBLE YEAR."

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1290 PRINT "THE DEPRECIABLE AMOUNT IS "K1
1300 RETURN
1310 REM ==DEPREN. FOR NPV-IRR==
1320 DP(0,0) = K1
1330 FOR L = 1 TO N
1340 DP(0,L) = DP(0,L - 1) - C(0,L)
1350 IF DP(0,L) > 0 THEN D(0,L) = 0
1360 IF DP(0,L) < = 0 THEN D(0,L) = C(0,L) - DP(0,L - 1): GOTO 1390
1370 NEXT L
1380 GOTO 1415
1390 FOR L1 = L + 1 TO N
1400 D(0,L1) = C(0,L1)
1410 NEXT L1
1415 C(0,N) = C(0,N) + WC
1420 RETURN
1430 REM ==WC FOR NPV-IRR==
1440 RM = 5640 * CE * 7 * CU(1) / 600
1450 FG = VC(1) * CU(1) * FO / 600 + FC / 6
1460 WC = RM + FG
1480 RETURN
1490 REM ==TAX FOR NPV-IRR==
1500 PRINT "TAXES WILL BE DEDUCTED AFTER ONE YEAR."
1510 INPUT "ENTER THE TAX RATE EG.50% AS 50 ";TB:TA = TB / 100
1520 FOR L4 = 1 TO N
1530 T(0,L4 + 1) = D(0,L4) * TA
1540 X(0,L4) = C(0,L4) - T(0,L4)
1550 NEXT L4
1560 X(0,N + 1) = - T(0,N + 1)
1570 N = N + 1
1580 RETURN
1590 REM ==NO TAX FOR NPV==
1600 FOR L5 = 1 TO N
1610 X(0,L5) = C(0,L5): NEXT L5
1620 RETURN
1630 REM ==IRR EXTRAPOLATION==
1640 IF R(S) > R(S - 1) THEN R = R(S) + .25: GOTO 1660
1650 IF R(S) < R(S - 1) THEN R = R(S) - .25: GOTO 1660
1660 RETURN
1670 REM ==NPV ROUTINE==
1680 H = 0:F = 0:D = 0
1690 FOR I2 = 1 TO N
1700 D = (1 + R / 100) ^ I2
1710 F = X(0,I2) / D:H = H + F
1720 NEXT I2
1730 V = H - K
1740 PRINT ">> NPV @ "R"%","IS " INT (V * 100 + .5) / 100; TAB( 30)" <<"
1750 RETURN
1760 REM ==Q ROUTINE==
1770 PRINT " TYPE": PRINT " 0 FOR YES": PRINT " 1 FOR NO"
1780 RETURN
1790 HOME
1800 PRINT "WELCOME TO THE LAND OF SENSEAN !!": PRINT : PRINT : PRINT
1810 PRINT : PRINT : PRINT : PRINT

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1820 PRINT "SENSEAN CALCULATES THE % CHANGE IN NPV": PRINT : PRINT "WITH THE ASSOCIATED "
      CHANGE IN EITHER": PRINT : PRINT TAB( 20)"OUTPUT PRICE": PRINT : PRINT TAB( 20)"C
      PACITY UTILITY": PRINT
1825 PRINT TAB( 20)"CAPITAL": PRINT : PRINT TAB( 20)"FIXED COST": PRINT : PRINT TAB(
      7)"OR VARIABLE COST": PRINT
1830 PRINT : PRINT "<=YOU MAY CHOOSE THE % CHANGE RANGE>="
1840 PRINT : PRINT
1850 INPUT "ENTER THE DISCOUNT RATE IN % ";R
1860 HOME : GOSUB 2960: PRINT
1870 Y$ = "Y":N$ = "N"
1880 INPUT "PRESS <RETURN> KEY WHEN READY TO START ";Q$
1890 P$ = "PRICE":V$ = "VAR COST":C$ = "CAP USE":E$ = "POWER":L$ = "LIN":LB$ = "LAB":CA$
      "CAPITAL":F$ = "FIX COST"
1900 HOME : PRINT "WHICH SENSITIVITY ANALYSIS DO YOU WISH TO PERFORM ?": PRINT
1910 PRINT " TYPE": PRINT TAB( 9)"PRICE FOR PRICE": PRINT TAB( 9)"CAP USE FOR CAPAC
      TY UTILITY": PRINT TAB( 9)"VAR COST FOR VARIABLE COSTS": PRINT TAB( 9)"CAPITAL FOR
      CAPATAL COST": PRINT TAB( 9)"FIX COST FOR FIXED COST": PRINT
1920 INPUT Q$
1930 IF Q$ < > P$ THEN IF Q$ < > C$ THEN IF Q$ < > V$ THEN IF Q$ < > CA$ THEN IF
      Q$ < > F$ GOTO 1900
1940 IF Q$ < > V$ GOTO 2020
1950 PRINT "DO YOU WISH TO EXAMINE THE EFFECT OF THE": PRINT "CONSTITUENT FACTORS OF THE
      VARIABLE COST ?": PRINT
1960 GOSUB 2930: INPUT Q6$: PRINT
1970 IF Q6$ < > Y$ THEN IF Q6$ < > N$ GOTO 1950
1980 IF Q6$ = N$ GOTO 2020
1990 PRINT "WHICH FACTOR DO YOU LIKE TO EXAMINE ?": PRINT : PRINT " TYPE": PRINT TAB(
      10)"POWER FOR POWER,": PRINT TAB( 10)"LIN FOR LIN CONSUMPTION,": PRINT TAB( 10
      "LAB FOR LABOUR.": PRINT
2000 INPUT Q$
2010 IF Q$ < > E$ THEN IF Q$ < > L$ THEN IF Q$ < > LB$ GOTO 1990
2020 HOME
2030 PRINT "A RANGE OF % CHANGE IN "Q$: PRINT "WILL BE USED"
2040 PRINT "THE RANGE WILL BE SET AT -30% TO +30%": PRINT "IF NOT SET BY YOU": PRINT
2050 PRINT "DO YOU WISH TO CHOOSE THE RANGE ?": PRINT
2060 GOSUB 2930: INPUT Q1$
2070 IF Q1$ = Y$ GOTO 2100
2080 IF Q1$ = N$ THEN E3 = - 30:E4 = 30: GOTO 2120
2090 IF Q1$ < > Y$ THEN IF Q1$ < > N$ GOTO 2050
2100 INPUT "ENTER THE LOWER LIMIT EG.-25% AS -25 ";E3: PRINT
2110 INPUT "ENTER THE UPPER LIMIT EG.+30% AS 30 ";E4: PRINT
2120 PRINT "DO YOU WISH TO CHOOSE THE INCREMENT STEP ?": PRINT
2130 PRINT "THE INCREMENT STEP WILL SET AT 10% IF NOT CHOSEN BY YOU": PRINT
2140 GOSUB 2930: INPUT Q2$: PRINT
2150 IF Q2$ = Y$ GOTO 2180
2160 IF Q2$ = N$ THEN W2 = 10: GOTO 2190
2170 IF Q2$ < > Y$ THEN IF Q2$ < > N$ GOTO 2120
2180 INPUT "ENTER THE INCREMENT STEP ";W2: PRINT
2190 Y(2) = E3:W3 = ((E4 - E3) / W2) + 2
2200 FOR J2 = 3 TO W3
2210 Y(J2) = Y(J2 - 1) + W2
2220 NEXT J2
2230 IF Q$ = P$ THEN GOSUB 2600: GOTO 2300
2240 IF Q$ = C$ THEN GOSUB 2680: GOTO 2300

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2250 IF Q$ = V$ THEN GOSUB 2760: GOTO 2300
2260 IF Q$ = E$ THEN GOSUB 3770: GOTO 2300
2270 IF Q$ = L$ THEN GOSUB 3830: GOTO 2300
2280 IF Q$ = LB$ THEN GOSUB 4000: GOTO 2300
2285 IF Q$ = F$ THEN GOSUB 4500: GOTO 2300
2290 IF Q$ = CA$ THEN GOSUB 4100: GOTO 2310
2300 GOSUB 4060
2310 HOME : GOSUB 1250
2320 GOSUB 3410
2330 GOSUB 1280
2340 GOSUB 3270
2350 PRINT
2360 PRINT "DO YOU WISH TO INCLUDE TAX ?": PRINT
2370 GOSUB 2930: INPUT QC$: PRINT
2380 IF QC$ = Y$ THEN GOSUB 3580
2390 IF QC$ = N$ THEN GOSUB 3700
2395 IF QC$ < > Y$ THEN IF QC$ < > N$ GOTO 2360
2400 IF Q$ = CA$ THEN GOSUB 4170
2410 GOSUB 2840
2420 PRINT
2430 INPUT "PRESS <RETURN> KEY TO VIEW TABLE": Q5$
2440 HOME
2450 GOSUB 3080
2460 INPUT "PRESS <RETURN> KEY TO CONTINUE ": Q5$
2470 HOME
2475 IF QC$ = Y$ THEN N = N - 1
2480 PRINT "DO YOU WISH TO PERFORM MORE SENSITIVITY ANALYSIS ?": PRINT
2490 GOSUB 2930: INPUT Q3$: PRINT
2500 IF Q3$ = Y$ GOTO 1900
2505 IF Q3$ < > Y$ THEN IF Q3$ < > N$ GOTO 2480
2510 PRINT "DO YOU WISH TO PERFORM NPV-IRR CALCULATIONS ?": PRINT
2520 GOSUB 2930: INPUT Q6$: PRINT
2530 IF Q6$ = Y$ GOTO 200
2535 IF Q6$ < > Y$ THEN IF Q6$ < > N$ GOTO 2510
2540 PRINT "DO YOU WISH TO PERFORM SHORT TERM": PRINT "BREAK-EVEN ANALYSIS ?": PRINT
2541 GOSUB 2930: INPUT QF$: PRINT
2542 IF QF$ = N$ GOTO 2570
2543 IF QF$ < > N$ THEN IF QF$ < > Y$ GOTO 2540
2544 GOSUB 4700
2550 PRINT "DO YOU WISH TO CONSIDER ANOTHER PROJECT ?": PRINT
2555 GOSUB 2930: INPUT Q4$: PRINT
2560 IF Q4$ = Y$ GOTO 40
2565 IF Q4$ < > Y$ THEN IF Q4$ < > N$ GOTO 2540
2570 HOME
2580 PRINT "THANK YOU & BYE-BYE"
2590 END
2600 REM ==PRICE ROUTINE==
2610 FOR J3 = 1 TO W3
2620 FOR J = 1 TO N
2630 P(J3) = P(1) * (Y(J3) + 100) / 100
2640 C(J3,J) = (P(J3) - VC(1)) * FD * CU(1) / 100 - FC
2650 NEXT J
2660 NEXT J3
2670 RETURN

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2680 REM ==CAPACITY UTILITY==
2690 FOR J4 = 1 TO W3
2700 FOR J = 1 TO N
2710 CU(J4) = CU(1) * (Y(J4) + 100) / 100
2720 C(J4,J) = (P(1) - VC(1)) * FD * CU(J4) / 100 - FC
2730 NEXT J
2740 NEXT J4
2750 RETURN
2760 REM ==VARIABLE COST==
2770 FOR J5 = 1 TO W3
2780 FOR J = 1 TO N
2790 VC(J5) = VC(1) * (Y(J5) + 100) / 100
2800 C(J5,J) = (P(1) - VC(J5)) * FD * CU(1) / 100 - FC
2810 NEXT J
2820 NEXT J5
2830 RETURN
2840 REM ==NPV ROUTINE==
2850 FOR J6 = 1 TO W3
2855 H = 0
2860 FOR J1 = 1 TO N
2870 D = (1 + R / 100) ^ J1
2880 F = X(J6,J1) / D: H = H + F
2890 NEXT J1
2900 V(J6) = H - K(J6)
2910 NEXT J6
2920 RETURN
2930 REM ==Q ROUTINE==
2940 PRINT " TYPE ": PRINT "      Y FOR YES": PRINT "      N FOR NO "
2950 RETURN
2960 REM ==PRINT FORMAT==
2970 PRINT "SUMMARY OF THE DATA YOU'VE INPUT": PRINT
2980 PRINT "PROJECT LIFE" TAB( 23);N; TAB( 30)"YEARS": PRINT
2990 PRINT "TOTAL INVESTMENT" TAB( 23);K1: PRINT
3000 PRINT "TAX RATE" TAB( 23);TB; TAB( 30)" %": PRINT
3010 PRINT "DESIGN CAPACITY" TAB( 23);CE; TAB( 30)"T.P.H.": PRINT
3020 PRINT "CAPACITY UTILITY" TAB( 23);CU(1); TAB( 30)" %": PRINT
3030 PRINT "OUTPUT PRICE" TAB( 23);P(1); TAB( 30)"PER TONNE": PRINT
3040 PRINT "VARIABLE COST" TAB( 23);VC(1); TAB( 30)"PER TONNE": PRINT
3050 PRINT "TOTAL FIXED COSTS" TAB( 23);FC; TAB( 30)"PER ANNUM": PRINT
3060 PRINT "DISCOUNT RATE" TAB( 23);R; TAB( 30)" %": PRINT
3070 RETURN
3080 REM ==SEN ANA TABLE==
3090 PRINT TAB( 10)"SENSITIVITY ANALYSIS": PRINT TAB( 18)"FOR": PRINT TAB( 16)Q$: PRI

3100 PRINT "*****"
3110 PRINT TAB( 1);Q$; TAB( 10);"% CHANGE"; TAB( 20);" NPV"; TAB( 30);"% CHANGE"
3120 PRINT "-----"
3130 FOR J7 = 1 TO W3
3140 IF Q$ = P$ THEN M(J7) = P(J7): GOTO 3210
3150 IF Q$ = C$ THEN M(J7) = CU(J7): GOTO 3210
3160 IF Q$ = V$ THEN M(J7) = VC(J7): GOTO 3210
3170 IF Q$ = L$ THEN M(J7) = LN(J7): GOTO 3210
3180 IF Q$ = E$ THEN M(J7) = E(J7): GOTO 3210
3190 IF Q$ = CA$ THEN M(J7) = K(J7): GOTO 3210

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3200 IF Q$ = LB$ THEN M(J7) = LB(J7): GOTO 3210
3205 IF Q$ = F$ THEN M(J7) = FC(J7): GOTO 3210
3210 V1 = (V(J7) / V(1) - 1) * 100
3220 PRINT TAB( 2);M(J7); TAB( 13); INT (Y(J7)); TAB( 20); INT (V(J7)); TAB( 30); INT (
1 * 100 + .5) / 100
3230 NEXT J7
3240 PRINT
3250 PRINT "*****"
3260 RETURN
3270 REM ==DEPREN. FOR S.A.==
3280 FOR L2 = 1 TO W3
3290 DP(L2,0) = K1
3295 C(L2,N) = C(L2,N) - WC(L2)
3300 FOR L = 1 TO N
3310 DP(L2,L) = DP(L2,L - 1) - C(L2,L)
3320 IF DP(L2,L) > 0 THEN D(L2,L) = 0: GOTO 3340
3330 IF DP(L2,L) < = 0 THEN D(L2,L) = C(L2,L) - DP(L2,L - 1): GOTO 3360
3340 NEXT L
3350 GOTO 3385
3360 FOR L1 = L + 1 TO N
3370 D(L2,L1) = C(L2,L1)
3380 NEXT L1
3385 C(L2,N) = C(L2,N) + WC(L2)
3390 NEXT L2
3400 RETURN
3410 REM ==WC FOR S.A.==
3420 RM = 5640 * CE * 7 / 6
3430 FG = VC(1) * FO / 6
3440 C2 = (RM + FG) * CU(1) / 100 + (FC / 6)
3450 FOR L3 = 1 TO W3
3460 IF Q$ < > CA$ GOTO 3480
3470 WC(L3) = C2: GOTO 3550
3480 IF Q$ < > C$ GOTO 3500
3490 WC(L3) = (RM + FG) * CU(L3) / 100 + FC / 6: GOTO 3550
3500 IF Q$ < > P$ GOTO 3520
3510 WC(L3) = (RM + FG) * CU(1) / 100 + FC / 6: GOTO 3550
3520 IF Q$ < > F$ GOTO 3528
3525 WC(L3) = (RM + FG) * CU(1) / 100 + FC(L3) / 6: GOTO 3550
3528 REM =FOR Q$=V$,E$,L$ & LB$=
3530 FG(L3) = VC(L3) * FO / 6
3540 WC(L3) = (RM + FG(L3)) * CU(1) / 100 + FC / 6
3550 C(L3,N) = C(L3,N) + WC(L3):K(L3) = K1 + WC(L3)
3560 NEXT L3
3570 RETURN
3580 REM ==TAX FOR S.A.==
3590 PRINT "TAXES WILL BE DEDUCTED AFTER ONE YEAR."
3600 INPUT "ENTER THE TAX RATE EG.50% AS 50 ";TB:TA = TB / 100
3610 FOR L6 = 1 TO W3
3620 FOR L7 = 1 TO N
3630 T(L6,L7 + 1) = D(L6,L7) * TA
3640 X(L6,L7) = C(L6,L7) - T(L6,L7)
3650 NEXT L7
3660 X(L6,N + 1) = - T(L6,N + 1)
3670 NEXT L6

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3680 N = N + 1
3690 RETURN
3700 REM ==NO TAX FOR S.A.==
3710 FOR L8 = 1 TO W3
3720 FOR L9 = 1 TO N
3730 X(L8,L9) = C(L8,L9)
3740 NEXT L9
3750 NEXT L8
3760 RETURN
3770 REM ==POWER ROUTINE==
3780 IF CE = 1 THEN R1 = .0976:R2 = 1 - R1: GOTO 3810
3790 IF CE = 2 THEN R1 = .0648:R2 = 1 - R1: GOTO 3810
3800 IF CE = 3 THEN IF MI = 2 THEN R1 = .057:R2 = 1 - R1: GOTO 3810
3805 IF CE = 3 THEN IF MI = 3 THEN R1 = .0533:R2 = 1 - R1
3810 GOSUB 3890
3820 RETURN
3830 REM ==LIN ROUTINE==
3840 IF CE = 1 THEN R1 = .6482:R2 = 1 - R1: GOTO 3870
3850 IF CE = 2 THEN R1 = .7186:R2 = 1 - R1: GOTO 3870
3860 IF CE = 3 THEN IF MI = 2 THEN R1 = .7178:R2 = 1 - R1: GOTO 3870
3865 IF CE = 3 THEN IF MI = 3 THEN R1 = .7563:R2 = 1 - R1
3870 GOSUB 3890
3880 RETURN
3890 REM ==SUB-LIN/POWER ROUTINE==
3900 FOR J = 1 TO W3
3910 FOR J1 = 1 TO N
3920 R(J) = (Y(J) + 100) * R1 / 100
3930 LN(J) = R(J) * VC(1):E(J) = LN(J):LB(J) = LN(J)
3940 VC(J) = (R(J) + R2) * VC(1)
3960 C(J,J1) = (P(1) - VC(J)) * FD * CU(1) / 100 - FC
3970 NEXT J1
3980 NEXT J
3990 RETURN
4000 REM ==LABOUR ROUTINE==
4010 IF CE = 1 THEN R1 = .1552:R2 = 1 - R1: GOTO 4040
4020 IF CE = 2 THEN R1 = .1069:R2 = 1 - R1: GOTO 4040
4030 IF CE = 3 THEN IF MI = 2 THEN R1 = .0892:R2 = 1 - R1: GOTO 4040
4035 IF CE = 3 THEN IF MI = 3 THEN R1 = .075:R2 = 1 - R1
4040 GOSUB 3890
4050 RETURN
4060 REM ==K TO K(I) ==
4070 FOR I = 1 TO W3
4080 K(I) = K: NEXT I
4090 RETURN
4100 REM == K ROUTINE 1 ==
4110 C1 = (P(1) - VC(1)) * FD * CU(1) / 100 - FC
4120 FOR J = 1 TO W3
4130 FOR J1 = 1 TO N
4140 C(J,J1) = C1: NEXT J1
4150 NEXT J
4160 RETURN
4170 REM = K ROUTINE 2 ==
4180 FOR I = 1 TO W3
4190 K(I) = K(I) * (Y(I) + 100) / 100

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4200 NEXT I
4210 RETURN
4500 REM ==FC ROUTINE==
4510 C3 = (P(1) - VC(1)) * FO * CU(1) / 100
4520 FOR I = 1 TO W3
4530 FC(I) = FC * (Y(I) + 100) / 100
4540 FOR J = 1 TO N: C(I,J) = C3 - FC(I): NEXT J
4550 NEXT I
4560 RETURN
4600 REM =CALC. C(0,I)'S FOR NPV=
4610 C4 = (P(1) - VC(1)) * FO * CU(1) / 100 - FC
4620 PRINT "CASH FLOWS CALCULATED FROM THE DATA": PRINT "-----"
4630 PRINT "YEAR", "CASH FLOW"
4631 PRINT "-----", "-----"
4635 FOR I = 1 TO N: C(0,I) = C4: PRINT I, C(0,I): NEXT I
4640 RETURN
4700 REM =S.T. B/E ANALYSIS=
4710 PRINT "=:SHORT TERM BREAK-EVEN ANALYSIS=:": PRINT
4720 PRINT "ENTER THE DESIRED RATE OF RETURN ON ": INPUT "INITIAL INVESTMENT IN % "; RI1: R
    I = RI1 / 100: PRINT
4730 VD = FO * CU(1) / 100
4740 G1 = (1 - 1 / (1 + RI) ^ N) / RI
4745 G = (K1 + WC) / G1 + FC
4750 FOR I = 1 TO 5
4760 Z(I) = (I * 10) - 30: Z(I) = 1 + Z(I) / 100
4770 PR(I) = P(1) * Z(I): VD(I) = VD * Z(I)
4780 BP(I) = FC / VD(I) + VC(1)
4785 IF PR(I) < = VC(1) GOTO 4810
4790 BV(I) = FC / (PR(I) - VC(1))
4800 BW(I) = G / (PR(I) - VC(1))
4810 BQ(I) = G / VD(I) + VC(1)
4820 NEXT I
4830 PRINT "SHORT TERM BREAK-EVEN ANALYSIS": PRINT "-----"
4840 PRINT "=:NO RETURN ON INITIAL CAPITAL=:": PRINT
4850 PRINT "AT PRICE" TAB( 10) "B/E VOL." TAB( 20) "AT VOL." TAB( 30) "B/E PRICE": PRINT "-----"
    PRINT TAB( 10) "-----" TAB( 20) "-----" TAB( 30) "-----"
4860 FOR I = 1 TO 5
4870 PRINT INT (PR(I)) TAB( 10) INT (BV(I)) TAB( 20) INT (VD(I)) TAB( 30) INT (BP(I)): P
    INT
4880 NEXT I
4882 PRINT
4884 INPUT "PRESS <RETURN> TO CONTINUE TABLE "; QW$: PRINT
4890 PRINT "WITH "RI * 100"% RETURN ON INITIAL INVESTMENT": PRINT
4910 PRINT "AT PRICE" TAB( 10) "B/E VOL." TAB( 20) "AT VOL." TAB( 30) "B/E PRICE": PRINT "-----"
    PRINT TAB( 10) "-----" TAB( 20) "-----" TAB( 30) "-----"
4915 FOR I = 1 TO 5
4920 PRINT INT (PR(I)) TAB( 10) INT (BW(I)) TAB( 20) INT (VD(I)) TAB( 30) INT (BQ(I)): P
    INT
4930 NEXT I
4940 PRINT "-----"
4950 RETURN

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INVESTMENT SIMULATION

I.1 Introduction

The conventional method of sensitivity analysis offers limited value of risk analysis. It suffers a serious limitation of altering one variable at a time while keeping all the others unchanged of original values. This is not fully representative of the real situation. The simulation technique employed here, adapted from Hertz (180), makes provision for simultaneous variations in all the variables. The variables used in this technique are in the form of probability distributions, instead of the usual single value parameters. These probability distributions of the variables ensured that a more realistic market situation is represented by giving the most likely outcomes of the variables the highest probabilities, hence making them more significant in the simulation.

Having established the probability distributions for the variable, a random set of variable is selected, from which NPV is calculated. This procedure of random variable selection and NPV calculation is repeated a large number of times. The probability distribution of the calculated NPV's is then constructed which is the output of the simulation.

The simulation is only carried out with the plant combination which shows the most favourable potential in the conventional NPV evaluation which is Plant Combination III (see Chapter 7).

I.2 Investment Appraisal Criteria

The investment appraisal criteria used in the simulation is Net Present Value (NPV) of the project. Appendix H gives an account of NPV techniques of investment appraisal.

As assumed previous, a working capital of two months stock of raw material and finished goods is incurred at the beginning of the project, and it is recovered at the end of the project. A corporation tax rate of 52% is applicable to taxable cash flows, there is a twelve month delay in tax payment and the capital allowance is claimed in the earliest possible date (depending on the cash flows).

The basic formulae-used before introduction of tax are

$$NPV = -(K + WC) + \sum_{i=1}^N A_i \times V_R^i + WC \times V_R^N$$

where

K = capital cost;

WC = working capital;

A_i = taxable cash flow in year i,

V_Rⁱ = discount factor for R% and year i,

and N = project life in years.

and A's is defined as

$$A = (P - VC) \times \frac{CU}{100} \times C - FC$$

where

P = price of output per tonne,

VC = variable cost per tonne,

C = maximum design capacity,

CU = capacity utilisation,

and FC = fixed cost per annum.

The variable cost, VC, can again be divided into several components:

$$VC = VP + VL + VM + VE$$

where

VP = power consumption per tonne of output,

VL = liquid nitrogen consumption per tonne,

VM = direct labour cost per tonne,

and VE = other variable costs per tonne.

The effects of tax are accounted for by the computer program.

I.3 Probability Distributions of the Input Variables

The probability distributions for the variable are based on the initial single point estimates presented in Appendix G.

As mention earlier a probability distribution is a more realistic representation of actual situation than a single point value. However,

the establishment of probability distributions for several variables may not improve the simulation output. In this simulation, three variables are assumed to have a uniform distribution they are project life, N , discount rate, R , and other variable costs, VE . The reasons for their selection are detailed below.

Given the robustness of the engineering structures of the cryogenic grinding machinery, and from the historical experience of the life of rubber recycling plants, it is not unreasonable to assume that the machinery of the cryogrind process will last in excess of 10 years. Also, it is unlikely that the product from this plant i.e. premium grade fine rubber crumb, to be made obsolete by substitutions, although there is a fear of decreasing demand due to longer lasting tyres (183) and the changing habit of motorists. Hence, a 10 years project life with an uniform probability distribution can be expected.

The discount rate is a difficult parameter to estimate. As discussed in the Chapter 7, the discount rate not only differs from industry to industry and from company to company, it is also influenced by the general economy of the nation. In view of its highly complex and subjective nature, a single point value of 10% per annum is assumed. This is a real rate of return, hence represents a substantially high added premium over the prime bank leading rate.

Given that VE , other variable costs, represents only a minor proportion (about 11.5% of total variable cost), and the inevitable element of uncertainty in estimating the initial single point values of the components of the variable cost, it is questionable whether the establishment of a probability distribution for VE will improve or affect the accuracy of the NPV simulation. Hence a uniform distribution is assumed. The rest of the input data is in the form of probability distributions, with the most probable outcomes commanding the highest probabilities and the least having the lowest probabilities. The probability of the outcomes are estimated from the knowledge of the forces acting on the variables concerned, and also from the trend of the historical data of these variables.

a) Capital Cost, K

Due to the relatively accurate estimation of the initial value of K (in Appendix G), and the relatively simple engineering construction of

the plant (most components of the capital equipment are standard machinery), it is estimated that is a 50% probability that K will remain as quoted.

As in most manufacturing sectors, however, the cost of manufacturing the capital equipment, such as labour, material and energy, will increase in line with inflation. This will be passed on to the equipment buyer, and hence an increased K to the recycling rubber manufacturer. Further more, the K quoted is slightly out of date. Therefore, it is reckoned that there is a fair chance K will increase. Given the relatively simple engineering construction, the most likely percentage of increase is expected to be in the region of 10% to 20% from the presently quoted value. It is strongly believed that a 10% increase is more likely.

There is also a small chance that K may decrease. This may be possible, for example, when there is a keen competition in supplying the capital equipment, and there may be cheaper alternatives for the various components. One of latter possibilities is possible cheaper imported grinder, and pinned or toothed disk mills from continental Europe.

The estimated probability distribution for K is shown below:

<u>K (%)</u>	<u>probability</u>	<u>cumulative probability</u>
90	0.03	0.03
100	0.50	0.53
110	0.30	0.83
120	0.14	0.97
130	0.3	1.00

b) Price, P

Rubber crumb price has been the subject of discussion in Section 2.4b and Chapter 7. Suffice to mention here that rubber crumb price is strongly demand related, and that the outlook for an improved price level in the near future is grim.

The probability distribution constructed reflects this market situation, with 90% probability of P attaining £180 (per tonne of output rubber crumb) or less. The distribution has a strong lefthanded skew, emphasizing the relative likeliness for P lower than £180 level. £180 per tonne

is chosen as the peak, commanding 36% probability because the price for a relatively coarse crumb (size not clearly specified) has been reported recently (Oct. 1981) in Germany to be £180 per tonne, and a finer crumb (< 500 micron or 40 mesh) was priced at well over £200 per tonne in the Netherlands (Oct. 1981). Recent quotations from a UK supplier (181) for 30 and 40 mesh crumb were £210 and £230 per tonne respectively (June 1982). Given the composite nature of the output (see Chapter 7), this price level is justified. The 10% probability of P attaining more than £180 may be achieved through contracted work, which has been known to command better prices (141). Export to Europe, where price is reported to be higher (121), may also be a possibility.

The probability distribution for P is shown below:

<u>P (£)</u>	<u>probability</u>	<u>cumulative probability</u>
150	0.06	0.06
160	0.18	0.24
170	0.30	0.54
180	0.36	0.90
190	0.06	0.96
200	0.04	1.00

c) Fixed Costs, FC

Considerable effort has been ^{put} into deriving an accurate estimate for the fixed costs, hence, the most probable FC value is that quoted in Appendix G of the Report, commanding 59% probability. The likelihood of an increased FC is reckoned to be no more than 20%, which is inflation related.

There is also a small chance, 6%, of FC decreases by about 10% from the present quoted level. This may be materialised through reducing the administrative, technical and sales supports, and by reducing the liquid nitrogen storage tank rental (through careful negotiations with the liquid nitrogen suppliers, for example).

The derived probability distribution for FC is shown below:

<u>FC (%)</u>	<u>probability</u>	<u>cumulative probability</u>
90	0.06	0.06
100	0.59	0.65
110	0.31	0.96
120	0.04	1.00

d) Capacity Utilisation, CU

It is very unlikely that a 3 tonne per hour rubber recycling plant will operate at full capacity, given the current (and near future) soft rubber crumb demand, and the quantity of the output crumb produced (about 200 tonnes per working week). It is assumed that the most probable CU is in the region between 60% to 70% of the fully installed capacity. It is also assumed that it is more likely that the plant will operate at a lower CU than the most probable range (of 60% - 70%). It is unlikely that a CU of more than 90% (of full capacity) will be achieved. This situation is reflected in the probability distribution of FC shown below:

<u>FC (%)</u>	<u>probability</u>	<u>cumulative probability</u>
40	0.03	0.03
50	0.18	0.21
60	0.38	0.59
70	0.34	0.93
80	0.06	0.99
90	0.01	1.00

e) Variable Costs, VC

VC is dominated by the cost of liquid nitrogen consumed, VL (constituting 75.63% of the total VC). The other components which a probability distribution has been developed for, are power consumption, VP, and man power or labour requirements, VM. The cost of liquid nitrogen is essentially the cost of electricity used in its production, hence it is expected that the probability distribution for VL will be very similar to that for VP.

(i) Liquid Nitrogen and Power Consumption, VL and VP

The cost of electricity is expected to increase, but the magnitude of which is difficult to estimate with accuracy (related to the oil and gas prices, cost of other energy such as nuclear power, and the energy policy of the Government). However, an increase of between 10% to 30%

may be expected, with a more likely range of between 10% - 20%. A reduction in the cost of liquid nitrogen consumed may be realised through careful negotiations with the suppliers (as a 3 THP cryogenic tyre grinding plant will be a major liquid nitrogen user). These conditions are reflected in the probability distribution for both VP and VL shown below:

<u>VL & VP (%)</u>	<u>probability</u>	<u>cumulative probability</u>
90	0.03	0.03
100	0.35	0.38
110	0.33	0.71
120	0.26	0.97
130	0.03	1.00

(ii) Labour, VM

The cost of labour, VM is expected to increase in line with inflation which is reflected in the probability distribution shown below:

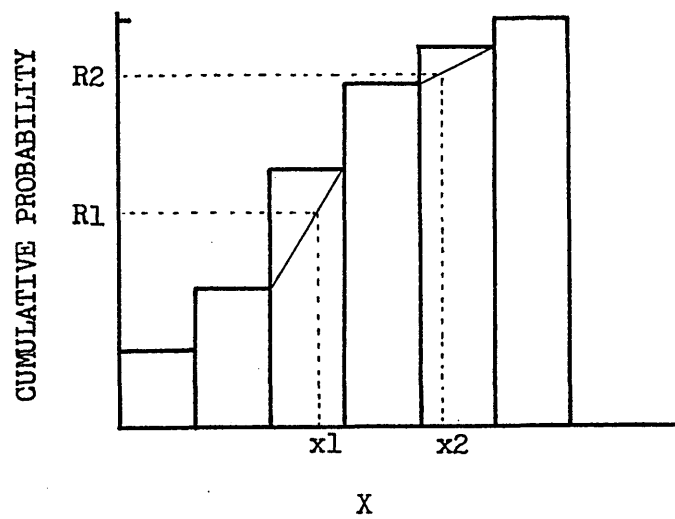
<u>VM (%)</u>	<u>probability</u>	<u>cumulative probability</u>
90	0.02	0.02
100	0.51	0.53
110	0.40	0.93
120	0.07	1.00

I.4 Method for Generating Random Variables

Since it is not possible to fit the empirically derived distribution of the variable with the standard well known probability distributions, such as normal & Poisson distributions, a generalise method for generating random variates from any distribution has been adapted (from Naylor et al (182), Chapter 4, p115). A slight modification has been made to the method.

The method is described below:

The discrete distribution (as those shown in Section I.3 above) is first converted into a cumulative distribution, as thus



R_i 's are random numbers between 0 and 1 generated by a random number generator.

A random number generator is used to generate random numbers between 0 and 1. These random numbers (eg. R_1 and R_2) are then converted, with interpolation, into their corresponding variates (eg. x_1 and x_2) as shown in the diagram.

Decreasing the variable interval in order to obtain a "better" set of random variables is of doubtful value because there is a degree of uncertainty in estimating the initial empirical distributions.

I.5 The Computer Program for Investment Simulation

A computer program is developed to perform the investment simulation for plant combination III (see Chapter 7). The flow diagram of the program is shown in Figure I.1.

The program initialises by reading the previously defined probability distributions of the variables (as done in Section I.3) into arrays, and the user inputs the number of repetitions, X , required. Using the method described in the previous section, a random set of K , P , CU , FC , VP , VL and VM is generated, and is used to calculate a NPV value. The working capital and the effects of taxation are fully accounted for in the program (through the I loop). The calculated NPV is stored in an element of an array. After repeating this process of random variable set selection and NPV calculation for X repetitions, the expected NPV value (the mean NPV in this case) and the standard deviation are calculated. The NPV's are then classified into 40 discrete groups with

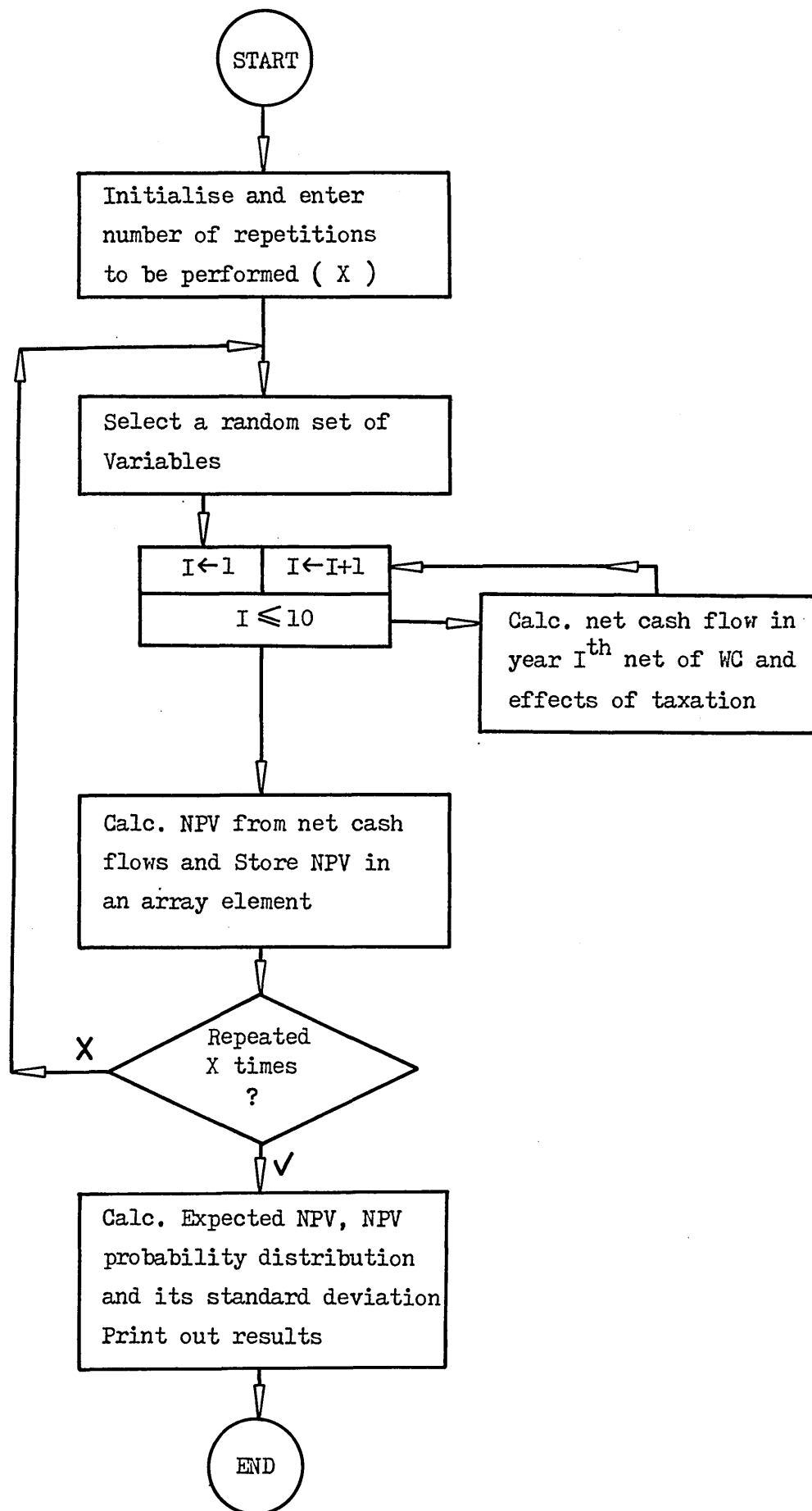


FIGURE I.1 Flow diagram of the Investment Simulation program.

their corresponding frequencies, hence arriving at a NPV probability distribution. This is then used to plot a graph of cumulative probability distribution of NPV,

The program was initially written for a 64K Apple Microcomputer, but the limited memory size and the extremely long running/processing time have prompted the transfer of the program to a mainframe computer (IBM 4341 VM/CMS).

One of the main requirements for this method of simulation is to ensure that a steady state has been reached. A steady state is reached when the results of repeated runs (expected NPV in this case) with a particular number of repetitions have stabilised to a constant value or, in practice, within a tolerable limit. This may be measured by the standard deviation of 5 such results. In order to determine the number of repetitions (X) at which steady state is reached, results of 5 repeating runs are obtained for a range of X's. X of 5000, 10000, 20000, 30000, 40000 and 50000 have been used. The standard deviations of the expected NPV's for each of the 5 runs are computed, and are plotted against their corresponding X's in Figure I.2.

It can be seen from the diagram that the fluctuation in the expected NPV's decreases rapidly as the number of repetitions (X) increases, and that a steady state has been reached after $X = 40000$. To ensure that the steady state is reached, X value of 100000 is to be used.

The program listing is presented at the end of this Appendix, Section I.6.

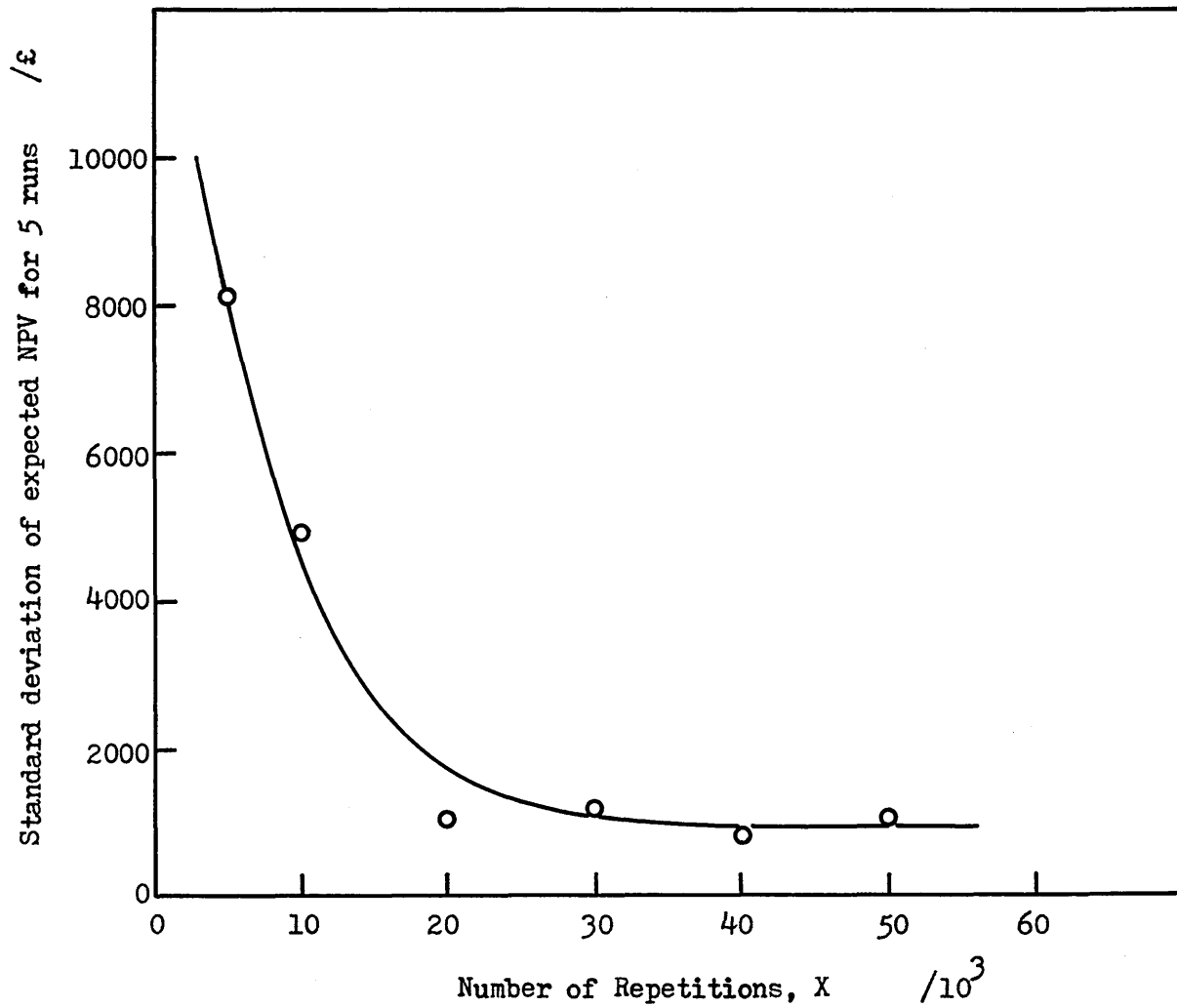


FIGURE I.2 Variation of standard deviation of expected NPV for five runs as a function of number of repetitions.

```

10 REM $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
20 REM $$
30 REM $ THIS IS THE FIRST STAGE $
40 REM $ OF $
50 REM $ THE INVESTMENT SIMULATION PROGRAM $
52 REM $
55 REM $ ( CORPORATE TAX RATE = 52% ) $
60 REM $
70 REM $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
80 REM
90 REM IT USES A SET OF PREDEFINED PROBABILITY DISTRIBUTIONS FOR
100 REM EACH OF THE VARIABLES INVOLVED I.E. CAPITAL, CRUMB PRICE,
110 REM CAPACITY UTILISATION, FIXED COSTS & VARIOUS COMPONENTS OF
120 REM THE VARIABLE COST.
130 REM
140 REM THE MAIN LIMITATION IS THE MAXIMUM NUMBER OF REPETITIONS
150 REM THAT THE PROGRAM CAN PERFORM. THIS LIMITATION IS
160 REM PRIMARILY DUE TO THE MEMORY SIZE OF THE INDIVIDUAL VM.
170 REM THE MAXIMUM NUMBER OF REPETITIONS IS ABOUT 100,000 LOOPS
180 REM
190 REM **NOTE**
200 REM SET MEMORY TO MAXIMUM AVAILABLE BY : SETUP STORE MAX
210 REM IN THE CMS ENVIRONMENT AND WAIT FOR STORE TO BE SET TO 1024K.
220 REM
230 REM
240 PRINT "ENTER NO. OF LOOPS (100,000 OR LESS)"
250 INPUT A1
260 A=A1/8
270 DIM T(15000),S(15000),U(15000),V(15000)
280 DIM W(15000),X(15000),Y(15000),Z(15000)
290 MAT S=(0)
300 MAT T=(0)
310 MAT U=(0)
320 MAT V=(0)
330 MAT W=(0)
340 MAT X=(0)
350 MAT Y=(0)
360 MAT Z=(0)
370 DIM F(41)
372 DIM D(11),H(11),I(11),J(11)
380 GOSUB 1210
390 GOSUB 1270
400 FOR J=1 TO 8
410 M=0
420 M=M+1
430 GOSUB 710
440 GOSUB 790
450 GOSUB 860
460 GOSUB 940
470 GOSUB 1020
480 C=(P-V)*C1-F
481 REM DEPRECIATION & TAX CALCULATIONS
482 GOSUB 4800
490 FOR I=1 TO 11
500 IF J=1 THEN W(M)=W(M)+H(I)/D(I)
510 IF J=2 THEN X(M)=X(M)+H(I)/D(I)
520 IF J=3 THEN Y(M)=Y(M)+H(I)/D(I)
530 IF J=4 THEN Z(M)=Z(M)+H(I)/D(I)
540 IF J=5 THEN S(M)=S(M)+H(I)/D(I)
550 IF J=6 THEN T(M)=T(M)+H(I)/D(I)

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570 IF J=8 THEN V(M)=V(M)+H(I)/D(I)
580 NEXT I
590 IF J=1 THEN W(M)=W(M)-K-W9
600 IF J=2 THEN X(M)=X(M)-K-W9
610 IF J=3 THEN Y(M)=Y(M)-K-W9
620 IF J=4 THEN Z(M)=Z(M)-K-W9
630 IF J=5 THEN S(M)=S(M)-K-W9
640 IF J=6 THEN T(M)=T(M)-K-W9
650 IF J=7 THEN U(M)=U(M)-K-W9
660 IF J=8 THEN V(M)=V(M)-K-W9
670 IF M < A GOTO 420
680 NEXT J
690 GOSUB 2120
700 GOTO 3510
710 REM RANDOM K
720 R=RND
730 FOR I = 2 TO 6
740 IF R<= G(I) & R> G(I-1) GOTO 760
750 NEXT I
760 K1=K(I-1)+I1*(R-G(I-1))/(G(I)-G(I-1))
770 K=K1*747373
780 RETURN
790 REM RANDOM PRICE
800 R=RND
810 FOR I= 2 TO 7
820 IF R<= L(I) & R> L(I-1) GOTO 840
830 NEXT I
840 P=P(I-1)+I2*(R-L(I-1))/(L(I)-L(I-1))
850 RETURN
860 REM RANDOM CAPACITY UTILISATION
870 R=RND
880 FOR I = 2 TO 7
890 IF R<= A(I) & R> A(I-1) GOTO 910
900 NEXT I
910 C2=C(I-1)+I3*(R-A(I-1))/(A(I)-A(I-1))
920 C1=C2*10998
930 RETURN
940 REM RANDOM FIXED COSTS
950 R=RND
960 FOR I= 2 TO 5
970 IF R<= E(I) & R> E(I-1) GOTO 990
980 NEXT I
990 F1=B(I-1)+I4*(R-E(I-1))/(E(I)-E(I-1))
1000 F=210000*F1
1010 RETURN
1020 REM RANDOM VARIABLE COSTS
1030 REM RANDOM VP
1040 R=RND
1050 FOR I= 2 TO 6
1060 IF R<= O(I) & R> O(I-1) GOTO 1080
1070 NEXT I
1080 V3=N(I-1)+L1*(R-O(I-1))/(O(I)-O(I-1))
1090 R=RND
1100 FOR I= 2 TO 6
1110 IF R<= O(I) & R> O(I-1) GOTO 1130
1120 NEXT I
1130 V4=N(I-1)+L1*(R-O(I))/(O(I)-O(I-1))
1140 R=RND
1150 FOR I= 2 TO 5
1160 IF R<= R(I) & R> R(I-1) GOTO 1180
1170 NEXT I

```

```

1180 V3=V3+V1*17+V2*V1*17+V1*17+V1*17
1190 V=V3*5.75+V4*81.54+V5*8.09+12.43
1200 RETURN
1210 REM DISCOUNT FACTOR CALCN.
1220 W=0.15
1230 FOR I=1 TO 11
1240 D(I)=(1+W)**I
1250 NEXT I
1260 RETURN
1270 REM K DISTRIBUTION
1280 K(1)=0.8
1290 K(2)=0.9
1300 K(3)=1.0
1310 K(4)=1.1
1320 K(5)=1.2
1330 K(6)=1.3
1340 G(1)=0
1350 G(2)=0.03
1360 G(3)=0.53
1370 G(4)=0.83
1380 G(5)=0.97
1390 G(6)=1.00
1400 I1=0.1
1410 REM P DISTRIBUTION
1420 P(1)=140
1430 P(2)=150
1440 P(3)=160
1450 P(4)=170
1460 P(5)=180
1470 P(6)=190
1480 P(7)=200
1490 L(1)=0
1500 L(2)=0.06
1510 L(3)=0.24
1520 L(4)=0.54
1530 L(4)=0.90
1540 L(6)=0.96
1550 L(7)=1.00
1560 I2=10
1570 REM CU DISTRIBUTION
1580 C(1)=0.3
1590 C(2)=0.4
1600 C(3)=0.5
1610 C(4)=0.6
1620 C(5)=0.7
1630 C(6)=0.8
1640 C(7)=0.9
1650 A(1)=0
1660 A(2)=0.03
1670 A(3)=0.21
1680 A(4)=0.59
1690 A(5)=0.93
1700 A(6)=0.99
1710 A(7)=1.00
1720 I3=0.1
1730 REM FC DISTRIBUTION
1740 B(1)=0.8
1750 B(2)=0.9
1760 B(3)=1.0
1770 B(4)=1.1
1780 B(5)=1.2
1790 E(1)=0

```

```

1800 E(2)=0.06
1810 E(3)=0.65
1820 E(4)=0.96
1830 E(5)=1.00
1840 I4=0.1
1850 REM VP & VL DISTRIBUTION
1860 N(1)=0.8
1870 N(2)=0.9
1880 N(3)=1.0
1890 N(4)=1.1
1900 N(5)=1.2
1910 N(6)=1.3
1920 O(1)=0
1930 O(2)=0.03
1940 O(3)=0.38
1950 O(4)=0.71
1960 O(5)=0.97
1970 O(6)=1.00
1980 L1=0.1
1990 REM VMAN DISTRIBUTION
2000 Q(1)=0.8
2010 Q(2)=0.9
2020 Q(3)=1.0
2030 Q(4)=1.1
2040 Q(5)=1.2
2050 R(1)=0
2060 R(2)=0.02
2070 R(3)=0.53
2080 R(4)=0.93
2090 R(5)=1.00
2100 L2=0.1
2110 RETURN
2120 REM CALC. NPV DISTRIBUTION
2130 S1=0
2140 S2=0
2150 S3=0
2160 S4=0
2170 S5=0
2180 S6=0
2190 S7=0
2200 S8=0
2210 FOR J=1 TO 8
2220 FOR I = 1 TO M
2230 IF J=1 THEN S1=S1+W(I)
2240 IF J=2 THEN S2=S2+X(I)
2250 IF J=3 THEN S3=S3+Y(I)
2260 IF J=4 THEN S4=S4+Z(I)
2270 IF J=5 THEN S5=S5+S(I)
2280 IF J=6 THEN S6=S6+T(I)
2290 IF J=7 THEN S7=S7+U(I)
2300 IF J=8 THEN S8=S8+V(I)
2310 NEXT I
2320 NEXT J
2330 S=S1+S2+S3+S4+S5+S6+S7+S8
2340 N=S/A1
2350 R1=N
2360 R2=N
2370 FOR J=1 TO 8
2380 IF J=1 THEN GOSUB 3030
2390 IF J=2 THEN GOSUB 3090
2400 IF J=3 THEN GOSUB 3150
2410 IF J=4 THEN GOSUB 3210

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```

2420 IF J=5 THEN GOSUB 3270
2430 IF J=6 THEN GOSUB 3330
2440 IF J=7 THEN GOSUB 3390
2450 IF J=8 THEN GOSUB 3450
2460 NEXT J
2470 B=(R2-R1)/40
2480 DIM M(10)
2490 MAT M=(0)
2500 V2=0
2505 Z=0
2510 Z=0
2520 MAT F=(0)
2530 FOR J=1 TO 8
2540 V1=0
2550 FOR I = 1 TO M
2560 IF J=1 THEN M(J)=(W(I)-N)**2
2570 IF J=2 THEN M(J)=(X(I)-N)**2
2580 IF J=3 THEN M(J)=(Y(I)-N)**2
2590 IF J=4 THEN M(J)=(Z(I)-N)**2
2600 IF J=5 THEN M(J)=(S(I)-N)**2
2610 IF J=6 THEN M(J)=(T(I)-N)**2
2620 IF J=7 THEN M(J)=(U(I)-N)**2
2630 IF J=8 THEN M(J)=(V(I)-N)**2
2640 V1=V1+M(J)
2650 IF J=1 THEN T1=(W(I)-R1)/B
2660 IF J=2 THEN T1=(X(I)-R1)/B
2670 IF J=3 THEN T1=(Y(I)-R1)/B
2680 IF J=4 THEN T1=(Z(I)-R1)/B
2690 IF J=5 THEN T1=(S(I)-R1)/B
2700 IF J=6 THEN T1=(T(I)-R1)/B
2710 IF J=7 THEN T1=(U(I)-R1)/B
2720 IF J=8 THEN T1=(V(I)-R1)/B
2730 T=INT(T1)+1
2740 IF T=41 THEN T=40
2750 F(T)=F(T)+1
2760 NEXT I
2770 V2=V2+V1
2780 NEXT J
2790 REM PRINT F(T)'S
2800 FOR I = 1 TO 40
2810 PRINT I,F(I)
2820 Z=Z+F(I)
2830 NEXT I
2840 V2=V2/A1
2850 PRINT
2860 PRINT "CUMULATIVE F(T)'S = ";Z
2870 PRINT
2880 PRINT "EXPECTED NPV = ";N
2890 PRINT
2900 PRINT "STD. DEVN. OF THE NPV DISTRIBUTION = ";SQR(V2)
2910 PRINT
2920 PRINT "RANGE = ";(R2-R1)
2930 PRINT
2940 PRINT "LOWER BOUND = ";R1
2950 PRINT
2960 PRINT "UPPER BOUND = ";R2
2970 PRINT
2980 PRINT "CLASS INTERVAL = ";B
2990 PRINT
3000 PRINT "NUMBER OF LOOPS = ";A1
3010 PRINT
3020 RETURN

```

```

3030 REM R1 R2 FOR HA(M)
3040 FOR I=1 TO M
3050 IF W(I)>=N & W(I)>R2 THEN R2=W(I)
3060 IF W(I)<N & W(I)<R1 THEN R1=W(I)
3070 NEXT I
3080 RETURN
3090 REM R1 R2 FOR HB(M)
3100 FOR I=1 TO M
3110 IF X(I)>=N & X(I)>R2 THEN R2=X(I)
3120 IF X(I)<N & X(I)<R1 THEN R1=X(I)
3130 NEXT I
3140 RETURN
3150 REM R1 R2 FOR HC(M)
3160 FOR I=1 TO M
3170 IF Y(I)>=N & Y(I)>R2 THEN R2=Y(I)
3180 IF Y(I)<N & Y(I)<R1 THEN R1 = Y(I)
3190 NEXT I
3200 RETURN
3210 REM R1 R2 FOR HD(M)
3220 FOR I=1 TO M
3230 IF Z(I)>=N & Z(I)>R2 THEN R2 =Z(I)
3240 IF Z(I)<N & Z(I)<R1 THEN R1 = Z(I)
3250 NEXT I
3260 RETURN
3270 REM R1,R2 FROM S(I)
3280 FOR I=1 TO M
3290 IF S(I)>=N & S(I)>R2 THEN R2=S(I)
3300 IF S(I)<N & S(I)<R1 THEN R1=S(I)
3310 NEXT I
3320 RETURN
3330 REM R1,R2 FROM T(I)
3340 FOR I=1 TO M
3350 IF T(I)>=N & T(I)>R2 THEN R2=T(I)
3360 IF T(I)<N & T(I)<R1 THEN R1=T(I)
3370 NEXT I
3380 RETURN
3390 REM R1,R2 FROM U(I)
3400 FOR I=1 TO M
3410 IF U(I)>=N & U(I)>R2 THEN R2=U(I)
3420 IF U(I)<N & U(I)<R1 THEN R1=U(I)
3430 NEXT I
3440 RETURN
3450 REM R1,R2 FROM V(I)
3460 FOR I=1 TO M
3470 IF V(I)>=N & V(I)>R2 THEN R2=V(I)
3480 IF V(I)<N & V(I)<R1 THEN R1=V(I)
3490 NEXT I
3500 RETURN
3510 PRINT "ANOTHER RUN ? (Y/N) "
3520 INPUT A$
3530 IF A$="Y" THEN 240
3540 GOTO 9999
4800 REM WORKING CAPITAL CALC.
4810 W9=118440*C2/6+V*C1/6+F/6
4840 MAT H=(O)
4860 FOR I=1 TO 10
4880 H(I)=C
4900 NEXT I
5000 MAT I=(O)
5020 D9=K
5030 REM DEPRECIATION CALCULATIONS
5040 FOR I=1 TO 10

```



```

5060 IF D9<=0 THEN I(I)=0 ELSE 5065
5062 GOTO 5180
5065 IF H(I)<=0 THEN I(I)=0 ELSE 5080
5070 GOTO 5180
5080 IF D9>H(I) THEN 5140
5100 I(I)=D9
5110 D9=0
5120 GOTO 5180
5140 I(I)=H(I)
5160 D9=D9-H(I)
5180 NEXT I
5200 REM TAX CALCULATIONS
5220 MAT J=(0)
5240 FOR I=1 TO 10
5260 IF (H(I)-I(I))>0 THEN J(I+1)=(H(I)-I(I))*0.52 ELSE J(I+1)=0
5280 NEXT I
5300 REM CASH FLOW AFTER TAX
5320 FOR I=1 TO 11
5340 H(I)=H(I)-J(I)
5360 NEXT I
5380 H(10)=H(10)+W9
5399 RETURN
9999 END

```

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A Paper Presented at the Plastics and Rubber Institute Annual National
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The relationship between properties-composition-processing conditions in rubber vulcanizates incorporating particulate scrap rubber are not understood. In this paper, we examine the influence of the amount of incorporated scrap rubber crumb and cure arrangements on the mechanical properties of these rubber-scrap rubber composites. The distribution of cure agent between crumb and matrix is described and the mechanical behaviour analysed in terms of the simple law of mixtures for composite materials.

INTRODUCTION

Although, a considerable amount of work has been done on the mechanics of rubber-composites containing high modulus glass beads (see, for example (1,2)), few systematic investigations have been reported of property relationships in rubber compounds incorporating particulate scrap rubber. Much of the data that has been given is essentially single point and at first sight appears to be conflicting. Furthermore, there has been little, or no, attempt to analyse the mechanical behaviour in terms of the theories of rubber elasticity or to identify the mechanisms responsible for this behaviour.

Rubber vulcanizates incorporating particulate scrap rubber crumb may be considered as rubber-rubber composites. Many theoretical models for property relationships in composite materials have been proposed. The simplest of these is based on the law of mixtures. One particular form of this law, used by McNally et al (3) as the basis for a model for short fibre-thermoplastic composites, is

$$E_{oc} = E_{om} (1 - \psi_f) + R E_{of} \psi_f \quad (1)$$

$$\sigma_{bc} = \sigma_{bm} (1 - \psi_f) + R' \sigma_{bf} \psi_f \quad (2)$$

where E_o is the initial elastic modulus, σ_b the tensile strength and ψ_f the volume fraction of filler. The meaning of the subscripts is; c - composite material, m - matrix material, f - filler. In the last case, for our systems, the filler is recycled rubber, indicated by RR. The parameters R and R' are termed reinforcement factors; $0 \leq R, R' \leq 1.0$. These are related to the adhesive bond strength at the matrix-crumb interface.

for the analysis of particulate filled systems. However, at this time our understanding of the properties of rubber-rubber composites does not warrant the use of more sophisticated models, such as the Kerner equation. Eqtns (1) and (2) should provide a suitable basis for analysis in our current work. Some justification for this assumption is given by the fact that the strength properties of NR and SBR vulcanizates incorporating RR crumb produced by the Trellfax process (4) closely follow eq. (2) with the parameters $\sigma_{bm} > \sigma_{bRR}$ and $R' = 1.0$.

The mechanical properties of rubber-scrap rubber crumb composites are governed by a multitude of variables, some of which cannot be quantified. These relate to the crumb (such as composition, size and size distribution, conditions experienced in service, and property degradation caused by the comminution process), the nature of the base (or matrix) rubber, the base rubber mix (compounding recipe) and the processing conditions (time, temperature, pressure).

In this investigation, we have held some of these variables at a constant level e.g. by incorporating the same type of crumb into different base rubbers using specified processing conditions. The purpose of the work was to identify mechanisms governing the mechanical behaviour of rubber-scrap rubber composites and examine the influence of cure arrangements (cure agent, content, cure time) on property values.

It is recognised that mathematical models based on the simple law of mixtures have limited use

Compound Preparation

The particulate scrap rubber used was 40 mesh ambient ground from whole tyre supplied by nlop Ltd. This was incorporated into three rubbers; SBR (1500), NR (Crusoe Standard wdered natural rubber) and SI (Dow-Corning 45 silicone rubber containing particulate silica reinforcement).

The SBR and NR compounds were mixed on a laboratory two-roll mill at about 50°C. The rubber crumb and curatives were added to pre-mixed batches and the compounds sheeted on the mill. The compounds were allowed to stand for hours at room temperature prior to vulcanisation in a hydraulic press. The moulded sheets, about 2 mm thick, were allowed to stand at room temperature overnight before testing.

SI compounds were mixed in the chamber of a RA Torque Rheometer and sheeted on a cooled mill. They were then moulded immediately. It was found that crosslinking could not be achieved if the compounds were allowed to stand. This indicated loss of cure agent (CA) from the rubber mix at room temperature. The moulded sheets were post cured at 100°C for 4 hours.

Compound recipes and cure conditions are given in Table 1. Because of the curing characteristics of SBR the cure time for these compounds varied according to the amount of CA incorporated into the mix. The objective was to optimise the cure of the base rubber. Below, we use the mass fraction of crumb incorporated into the mix, ϕ_{RR} phr, to describe the crumb content rather than, the more fundamental, the mass fraction of rubber hydrocarbon, ψ_{RR} .

Test Procedures

The mechanical properties were measured using standard dumb-bell samples at a strain rate of 10^{-3} s^{-1} . The results given below are the average values for six specimens and in all cases σ and ϵ represent engineering stress and strain. Structure and element distribution studies were made using a Philips PSEM500 SEM fitted with EDAX facility.

RESULTS AND DISCUSSION

Material Systems

To analyse the behaviour of these systems in terms of the mechanics of composites, it is necessary to have property values for the matrix and crumb. From data given in reference (5), it is estimated that typical average values for rubber would be approximately $E_0 = 4 \text{ MPa}$ and 20 MPa . It has not been possible to estimate the degree of property degradation caused by the grinding process but it was felt that for a simplistic analysis used here these values would serve as an indication of E_{ORR} and σ_{bRR} .

property values for the rubbers with no crumb addition can serve as indicators of matrix material properties. Typical values are given in Table 2.

Relative to the crumb, the gum SBR provided a low strength, low modulus matrix with the possibility of good interfacial adhesion ($R, R' \rightarrow 1$); the NR base provided comparable strength and low modulus, again with the possibility of good adhesion; the SI provided a low modulus, moderate strength base and poor interfacial adhesion ($R, R' \rightarrow 0$). Evidence for this observation is given in Figure 1.

General Observations

For a particular CA content the incorporation of rubber crumb produced the following behaviour. An increase in property value is indicated as + and a decrease as -.

SYSTEM	E_{oc}	σ_{bc}	ϵ_{bc}
SBR-RR	+	+	-
NR-RR	+	-	-
SI-RR	-	-	-

The enhancement of the E_{oc} values for the SBR-RR and NR-RR systems indicate some degree of bonding between the rubber matrix and the crumb, and that the crumb acts as a (relatively) high modulus filler. The depression of E_{oc} for the SI-RR system can be attributed to non-bonding, as was expected. Although the enhancement of σ_{bc} for SBR-RR indicates a reasonable degree of interfacial adhesion, no meaningful analysis of the strength properties of SBR-RR and NR-RR can be made at this stage.

Increasing the CA content at constant ϕ_{RR} produced:

SYSTEM	E_{oc}	σ_{bc}	ϵ_{bc}
SBR-RR	+	+	-
NR-RR	+	-	-
SI-RR	+	+	-

This type of behaviour was expected since increasing the curative content increased the crosslink density in the matrix material leading to an enhancement of E_{om} and the depression of ϵ_{bm} . The reasons for the decrease of σ_{bc} for the NR-RR are complex and no detailed explanation can be given.

Compounds of Constant Hardness

Results for the three composites are given in Table 3. These confirm some of the observations made above. It is seen for the SBR-RR system that to achieve the same hardness value the CA content decreased with increasing ϕ_{RR} . Indicating, again, that there was bonding between matrix and crumb and that the crumb acted as a high modulus filler. It is interesting to

stems this parameter decreased markedly with increasing ϕ_{RR} . It is also seen for the SBR-RR stem that the energy density to break, $= \sigma_b \epsilon_b / 2$, increased with increasing crumb content. This is the reverse of the behaviour served by Dreyfuss et al (2) who found that the incorporation of bonding and non-bonding glass spheres into a polybutadiene rubber increased U_b .

to achieve constant hardness with the NR-RR stems, the CA concentration remained approximately the same whereas for the SI-RR compounds the CA content had to be increased. In the second case, this can be attributed to a variety of causes, such as the presence of contaminants, the acidity of the mix and unsaturation in the rubber crumb.

The influence of CA content on property values, for different ϕ_{RR} has been investigated. In general terms, it was observed for the SBR-RR stems that E_{oc} and σ_{bc} increased monotonically with increasing S in the range S = 1-10 phr and decreased. For the NR-RR and SI-RR composites the property relationships were more complex.

Analysis of Stress-Strain Relationships

The σ - λ curves for SBR-RR, S = 1 phr shown in Fig. 2 can be used as the basis for discussion. The primary difference between the relationships for the crumb filled elastomers at high λ . This has been described previously, for glass bead filled rubber, e.g. (1, 2) and was attributed to bonding between matrix and filler.

In the current work two models have been used to analyse the σ - λ behaviours. The Mooney equation

$$\frac{\sigma}{2(\lambda - 1/\lambda^2)} = C_1 + \frac{C_2}{\lambda} \quad (3)$$

and a simplified form of the inverse Langevin function expression for non-Gaussian behaviour given by Kaelble et al (6). This can be written (7),

$$\frac{(1 - 1/\lambda)}{\sigma} = \frac{1}{E_L} - \frac{\lambda^2}{E_L \lambda^2 L} \quad (4)$$

where E_L and λ_L are the terminal modulus and terminal extension ratio respectively. λ_L is related to the number n of statistical links in a network chain by $\lambda_L^2 = n$. Eq. (4) has been successfully applied to the analysis of the σ - λ behaviour of S-B-S thermoplastic elastomers (7).

Mooney plots for SBR-RR systems with the same crumb agent content are given in Fig. 3. These plots are much the same as those described for other elastomeric materials (see for example Treloar (8)) except for $1/\lambda \rightarrow 0$. The reasons for this can be interpreted from the non-

Figs. 4 and 5.

For SBR-RR, S = 1.0, $\phi_{RR} = 0$ the plot shows a straight line relationship over a relatively large range of λ^2 values. However, with the crumb filled specimens there are marked deviations from this relationship. In the case of the Mooney plots, deviations from linearity with decreasing $1/\lambda$ are attributed to the onset of non-Gaussian behaviour (8) and it is possible to determine a value of the extension ratio, λ^* , at which this occurs. In a similar fashion, we might attribute the observed deviations from the non-Gaussian expression to debonding between matrix and filler. It is then possible to estimate a critical value of λ , i.e. λ_K , for this process. In addition, Mullins has described a procedure for the determination of the value of the number of statistical links in a network chain from λ^* . Consequently, it is possible to compare the value of n obtained in this way with that given by the modified Kaelble equation.

Values of network parameters for a range of SBR-RR composites evaluated using Eqns. (3) and (4) are summarised in Table 4. The values of λ^* and n (Mullins) were estimated using the Mullins procedure described by Treloar (8). It is seen that in general λ_L was significantly larger than λ_b , the values of λ_L , λ^* and λ_K decreased with increasing ϕ_{RR} and S, and that the values of n given by the two models were in reasonable agreement. It is interesting to note that the incorporation of crumb has the same effect on the value of n as increasing the CA contents.

A comparison is given below of the values of $1/\lambda_K$ obtained from the non-Gaussian plots and the values of $1/\lambda$ for zero gradient in the Mooney plots at $1/\lambda \rightarrow 0$. These points are indicated by arrows on Fig. 3.

SYSTEM	$1/\lambda_K$	$1/\lambda$ (Mooney)
S = 1, $\phi_{RR} = 20$	0.19	0.15
S = 1, $\phi_{RR} = 50$	0.22	0.20
S = 2, $\phi_{RR} = 20$	0.20	0.20
S = 2, $\phi_{RR} = 50$	0.24	0.25

Assuming our interpretation of λ_K is correct, it appears that the distortion in the Mooney plots at $1/\lambda \rightarrow 0$ can be attributed to debonding phenomena.

It is concluded that for $\lambda < \lambda_K$ the SBR-RR composites behave like homogeneous elastomeric networks exhibiting Gaussian and non-Gaussian type behaviour. At $\lambda \geq \lambda_K$ debonding between matrix and filler takes place so that the reinforcement factor R' in eq. (2) is less than unity. For high incorporations of CA, S = 5, 10 phr in this case, debonding does not occur. This is because the critical value of strain

propagation take place simultaneously as described, for example, by Eirich and Smith (9).

The dependence of λ_K on ϕ_{RR} has not yet been analysed in detail because of the lack of suitable data. However, the small decrease of λ_K with increasing ϕ_{RR} observed for the SBR-RR composites might be attributed either to a disruption of the cure process due to the presence of rubber crumb (e.g. migration of the cure agent from mix to crumb) or a strain magnification effect in the matrix. For example, Mullins (10) has proposed that for elastomers filled with rigid filler particles, the actual strain in the matrix material is given by $\epsilon' = \epsilon_f E_f / E_m$ where E_f and E_m are the modulus of the filled and unfilled rubber and ϵ_f is the measured strain for the composite. For the particular situation considered here, this equation can be rearranged to give the actual stress in the matrix material at the point of debonding, σ_{Km} , as

$$\sigma_{Km} = \epsilon'_f E_{om} = (\lambda_K - 1) E_{oc} \quad (5)$$

For the SBR-RR, $S = 1$ phr, $\phi_{RR} = 20, 50$ phr, and SBR-RR, $S = 2$ phr, $\phi_{RR} = 20, 50$ phr composites the values of σ_{Km} calculated in this way are in the range 6.2 - 6.5 MPa; the value increases in the order of materials stated. It would be too simplistic to directly associate these σ_{Km} values with the interfacial bond length between matrix and crumb. The Mullins equation clearly over-estimates strain magnification in rubber-rubber composites where the formation of the crumb makes some contribution to the overall strain. However, analyses along these lines might prove useful in studying interfacial phenomena in these material systems.

Up to the present time, no evidence for debonding has been found in the NR-RR and SI-RR systems. It is speculated that the reasons for this are that in the first case matrix-filler bonding occurs at the point of failure, and consequently does not influence the shape of the σ - λ curves, and in the second there is no interfacial adhesion between crumb and matrix, $\lambda_K \rightarrow 1.0$. In this case the system behaves as a cellular elastomer with rubber crumb filling the voids.

Cure Agent Distribution

The clearly demonstrated dependence of mechanical properties on the cure arrangements and the identification of a debonding process in SBR-RR leads to a consideration of the nature of the interfacial layer and the role of the cure agent.

It is well-established that to achieve optimum properties in vulcanizates incorporating crumb, it is necessary to increase the amount of CA in the base mix (11). It is also known that when using rubber mix-vulcanized rubber systems

of time (minutes) (12). It has been proposed (13) that there is a connection between curative diffusion and interfacial adhesion in that diffusion will give rise to an interfacial boundary layer depleted of CA. This layer will have strength properties inferior to those of the bulk matrix material. Another complication results from the temperature dependence of the relative solubility of CA in different rubbers (12).

We have investigated CA distribution using X-ray mapping and EDAX techniques. In the majority of cases, the maps indicate that, regardless of the amount of CA (either S or DCBP) incorporated into the mix, the CA concentration in the crumb is higher than that in the matrix.

The relative distribution of S in SBR-RR vulcanizates has been quantified by measuring the height of the S peak in the X-ray spectrum with background radiation subtracted. Line scans showing S peak height in SBR-RR, $S = 1.0$ phr, $\phi_{RR} = 0, 20, 50$ phr compounds are given in Fig. 5 where for the crumb filled materials the distribution is plotted as a function of distance, y/y_{max} , from the centre of the particle. The dimensions of the particles along the scan lines were; $\phi_{RR} = 20$ phr, $2y_{max} = 190 \mu m$ and $\phi_{RR} = 50$ phr, $2y_{max} = 160 \mu m$. It is seen that, for the most part, the S concentration remained approximately constant across the particle, there was a rapid change in S concentration at the particle matrix interface and that the S concentration in the matrix of crumb filled systems was less than that for unfilled gum SBR. Over a distance of $\sim 40 \mu m$ there is no indication of an S depleted boundary layer in the matrix adjacent to the crumb particle. In addition the S concentration in the crumb for the $\phi_{RR} = 50$ phr compound is less than that for the $\phi_{RR} = 20$ phr compound. This would be expected since there is more crumb to absorb the CA incorporated into the mix.

The quantitative accuracy of these results with respect to the amount of S present in the two material phases is uncertain. Because of the chemical similarity of the materials, it is felt that the ZAF correction will be small. What is more important is the size of the crumb particles relative to the electron capture volume in these low atomic number materials. It is easily demonstrated for these elastomers that the capture volume is much larger than the dimensions of the crumb particle. Consequently the values of the S peak X-ray count for the crumb will depend on the S concentration in both crumb and matrix, and possibly the amount of incorporated crumb. This implies that the relative concentration of S in the crumb estimated in this way is less than that actually present. Further investigation of this is needed.

qtms. (1) and (2) are clear. Because of curative diffusion from mix to crumb the value of σ_{bm} , and probably σ_{bm} , will decrease with increasing ψ_{RR} . Although it is not known if the CA diffused into the crumb is bound or free it is likely that a proportion will cause further crosslinking of the vulcanized crumb articles. Consequently E_{ORR} and σ_{ORR} will also depend on ψ_{RR} . How curative diffusion influences R and R' is not known; there is no evidence of an interfacial boundary layer. For the systems studied this may be smaller than the resolution of the measurement technique.

CONCLUSION

This paper describes the initial results of an investigation into the mechanics of rubber-particulate scrap rubber composites. The results show that for the systems studied the composites behave like conventional rubbers exhibiting Gaussian and non-Gaussian behaviour. However, in one system (SBR-RR), a process has been identified which can be attributed to debonding between matrix and crumb. Studies of cure agent distribution have shown enhanced levels of cure agent in the crumb (as expected) but there is little evidence of an interfacial boundary layer depleted of cure agent.

Bearing in mind the ultimate objective of this work, which is the development of formulations (both crumb characteristics and recipes) for the optimisation of the mechanical properties of compounds incorporating particulate scrap rubber, the results indicate several areas worthy of further systematic investigation. These include the role of the cure agent, particle-particle interaction, interfacial phenomena (e.g. debonding and the use of coupling agents) and the influence of the method of comminution (e.g. ambient/cryomilling).

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INGREDIENT	SBR-RR phr	NR-RR phr	SI-RR phr	SBR S=2.0phr	NR S=2.5phr	SI DCBP=0.45phr
se Rubber	100	100	100			
umb	0-50	0-50	0-50	E_o /MPa	1.0	1.4
nc oxide	5	5		σ_b /MPa	0.9	10.4
earic acid	2	2		ϵ_b	6.5	6.4
tioxidant	1	1				6.7
	1.0-10	2.5-10				
TS	1.5-1.88	1.0-1.25				
EC	0.2-0.25	0.1-0.13				
BP			0.15-18.8*			
RE						
me/min	30-15	15	10			
mp/°C	150	140	116			
essure/tpi	1.0	1.0	0.5			

ctive ingredient.

BLE 3 Mechanical Properties of Compounds having the same Hardness Value

R-RR ($E_{oc} = 2.1$ MPa)				NR-RR ($E_{oc} = 1.4$ MPa)			
/phr	0	20	50	ϕ_{RR} /phr	0	20	50
phr	8.5	4.0	2.0	S/phr	2.5	2.4	2.5
c/MPa	1.7	1.7	2.2	σ_{bc} /MPa	10.4	8.5	3.0
c	2.1	2.4	4.8	ϵ_{bc}	6.4	5.4	4.4
c/MJ m ⁻³	1.8	2.0	5.2	U_{bc} /MJ m ⁻³	33.0	23.0	6.6

SI-RR ($E_{oc} = 0.60$ MPa)				
ϕ_{RR} /phr	0	5	10	20
DCBP/phr	0.15	2.35	3.75	9.75
σ_{bc} /MPa	5.5	3.4	2.1	1.3
ϵ_{bc}	11.3	7.9	8.9	6.9
U_{bc} /MJ m ⁻³	31.1	13.4	9.4	4.5

S /phr	ϕ_{RR} /phr	λ_b	λ_L	λ^*	λ_K	n (n-G)	n (M)
1.0	0	8.8	13.9	5.0		192	>300
	20	7.8	8.9	3.2	5.4	80	124
	50	7.5	8.3	2.4	4.6	69	60
2.0	0	7.6	12.5	5.9		157	>300
	20	5.6	8.3	2.5	5.2	69	70
	50	5.7	6.9	2.1	4.1	47	45
5.0	0	3.9	8.7	2.4		75	60
	20	2.8	6.2	2.1	$>\lambda_b$	39	43
	50	2.9	5.3	1.7	$>\lambda_b$	28	<40
10.0	0	2.9	7.1			50	
	20	2.2	5.1		$>\lambda_b$	26	
	50	2.4	4.1		$>\lambda_b$	17	

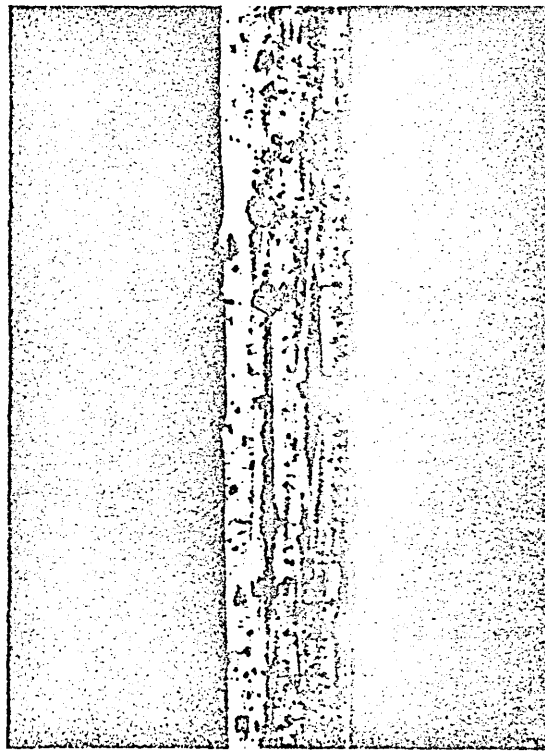


FIG 1. Macrophotograph of SI-RR, $\phi_{RR} = 5$ phr, under strain showing conical shaped voids and crumb particles

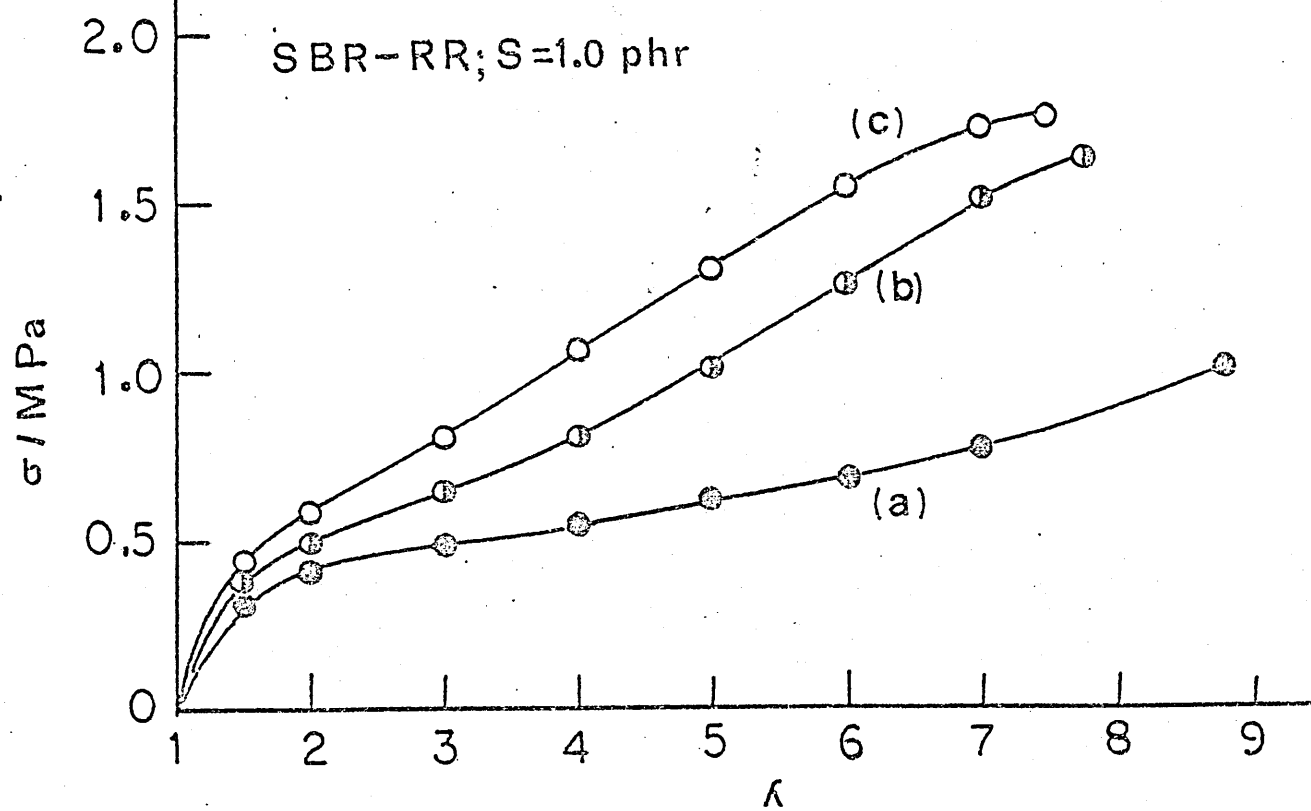


FIG 2. Stress-extension ratio curves for (a) $\phi_{RR} = 0$ phr, (b) $\phi_{RR} = 20$ phr and (c) $\phi_{RR} = 50$ phr

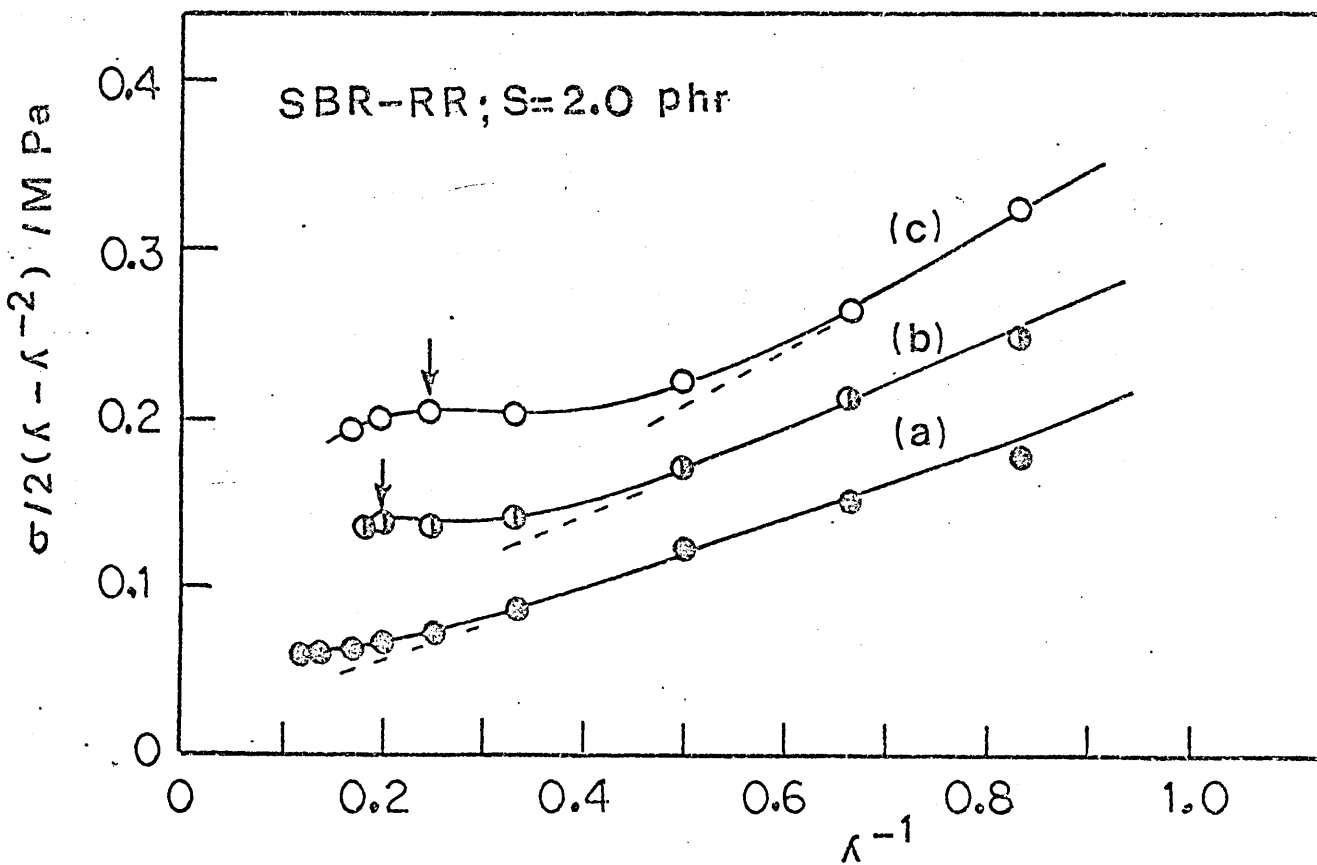


FIG 3. Mooney plots for (a) $\phi_{RR} = 0$ phr, (b) $\phi_{RR} = 20$ phr and (c) $\phi_{RR} = 50$ phr

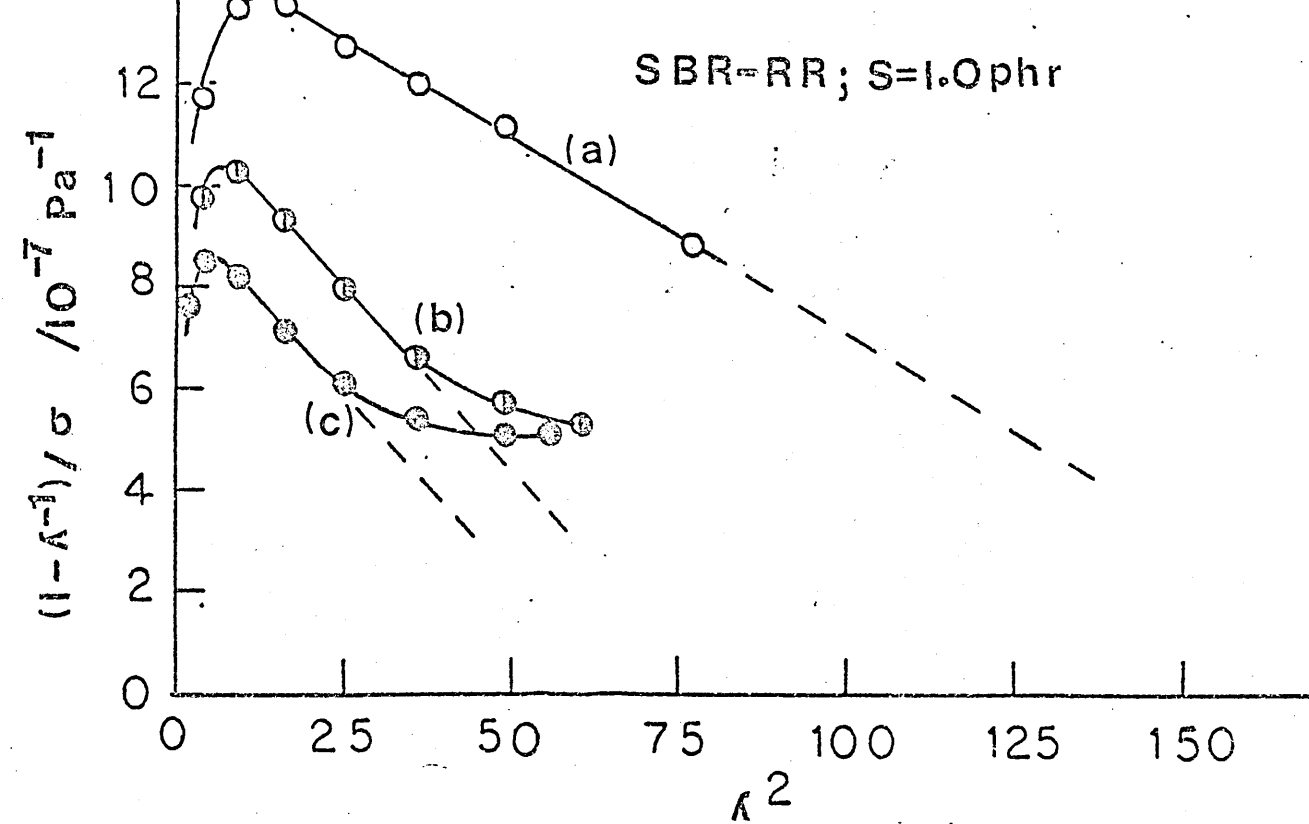


FIG. 4. Non-Gaussian plots for (a) $\phi_{RR} = 0$ phr, (b) $\phi_{RR} = 20$ phr and (c) $\phi_{RR} = 50$ phr

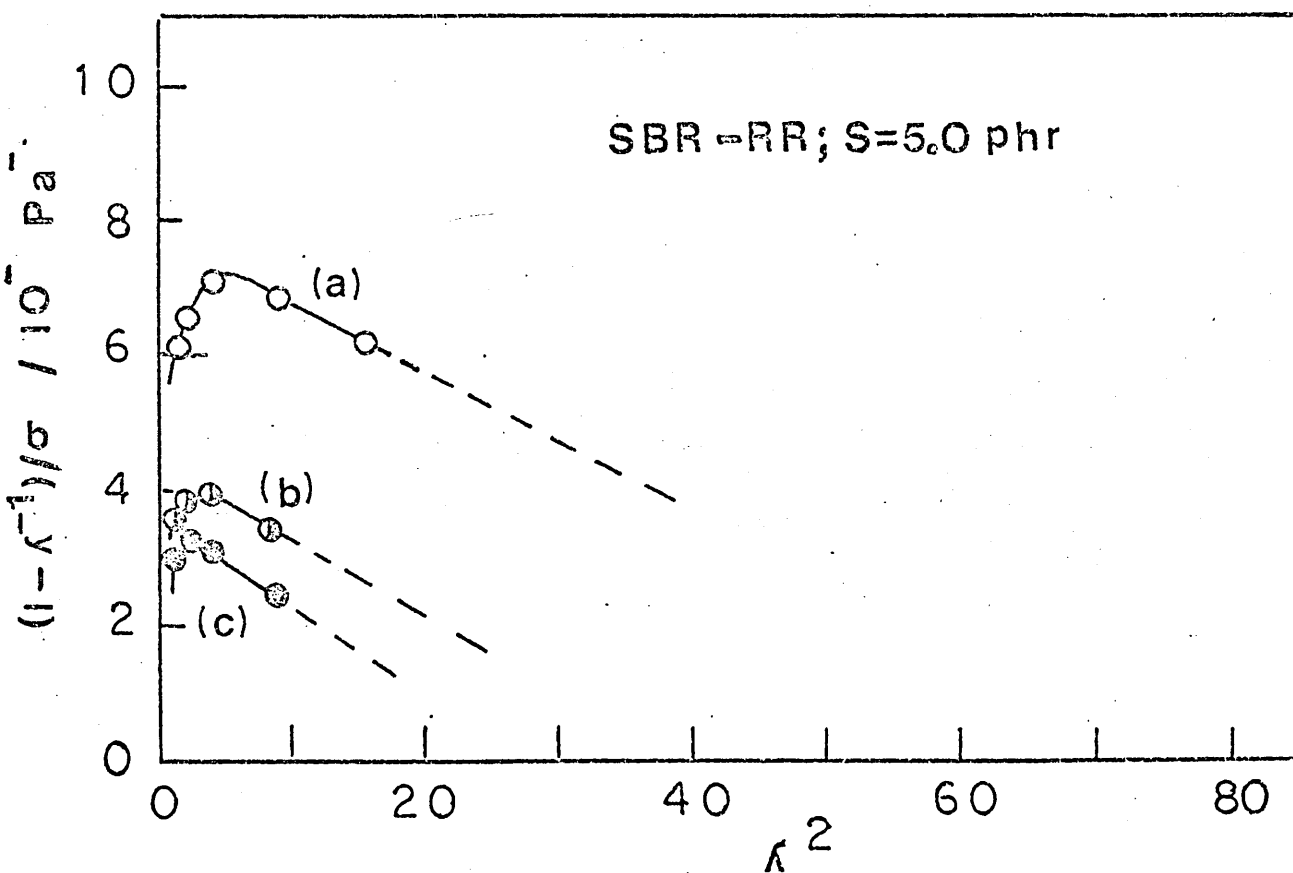


FIG. 5. Non-Gaussian plots for (a) $\phi_{RR} = 0$ phr, (b) $\phi_{RR} = 20$ phr, (c) $\phi_{RR} = 50$ phr

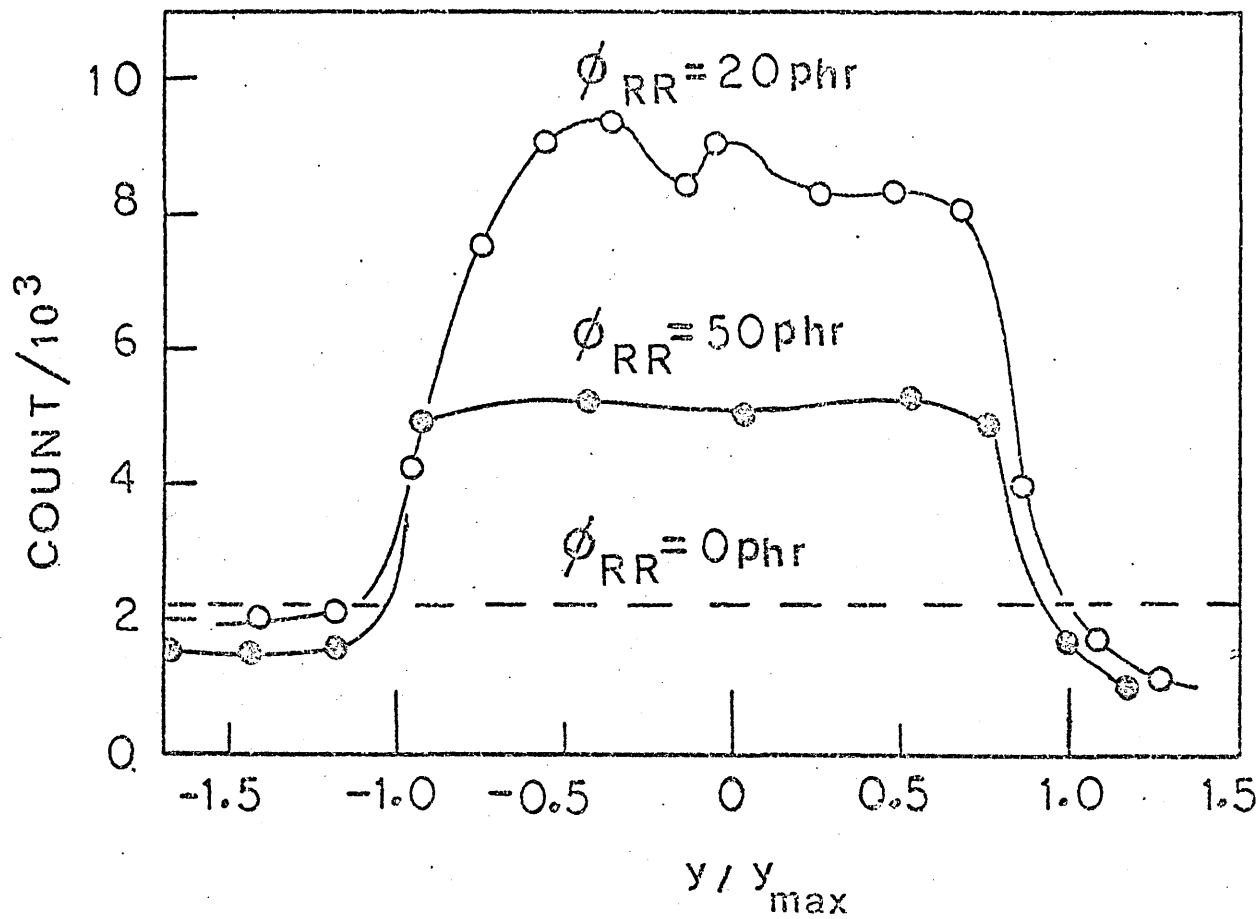


FIG. 6. Line scan of the integrated count in the $S K_{\alpha}$ peak of the X-ray spectrum for SBR-RR, $S = 1.0$ phr